# Summary of Forum 2008 Findings on Infrared Imaging of Exoplanets

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Missions 2010-2020 Workshop

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# Contributors

## 1.1 Contributors

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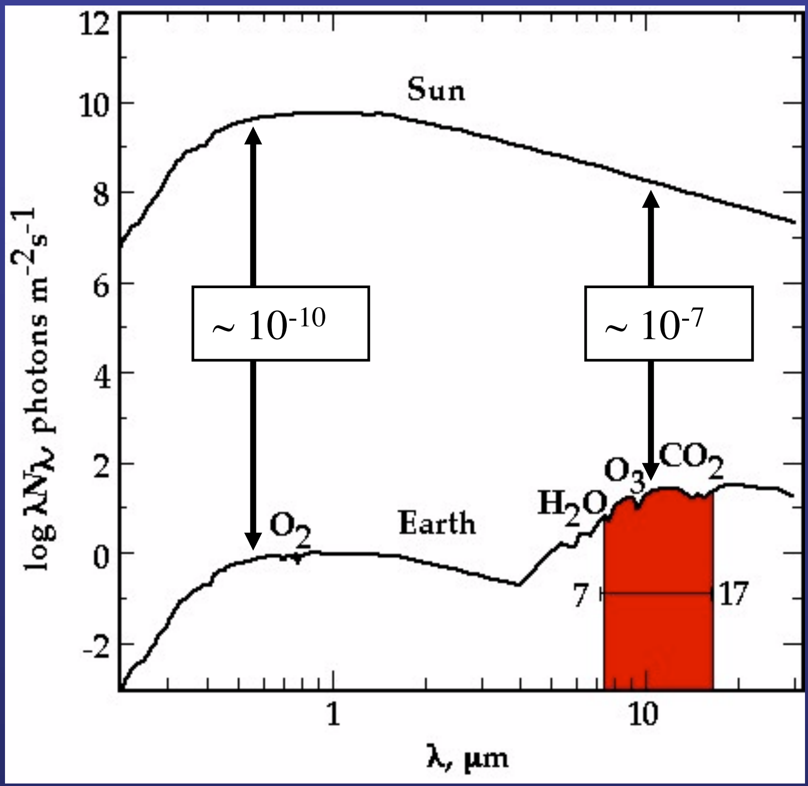
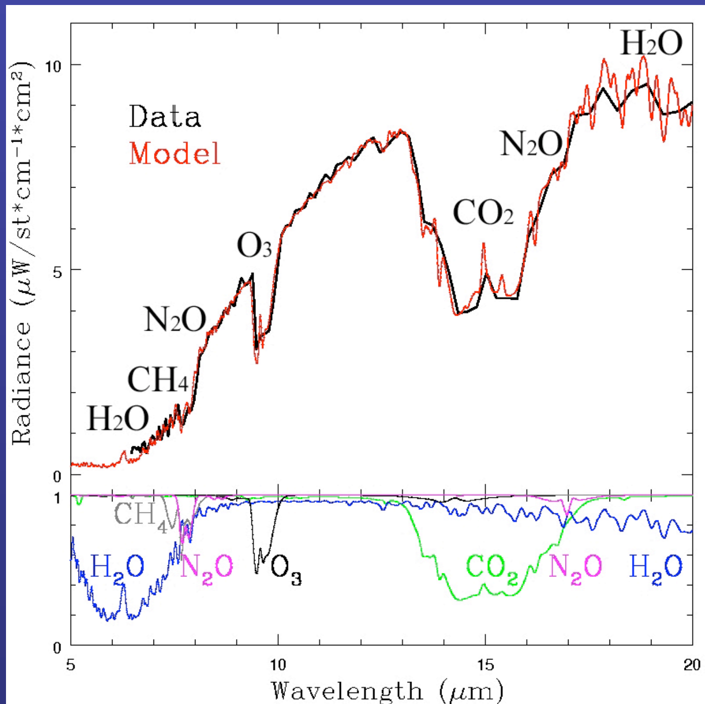
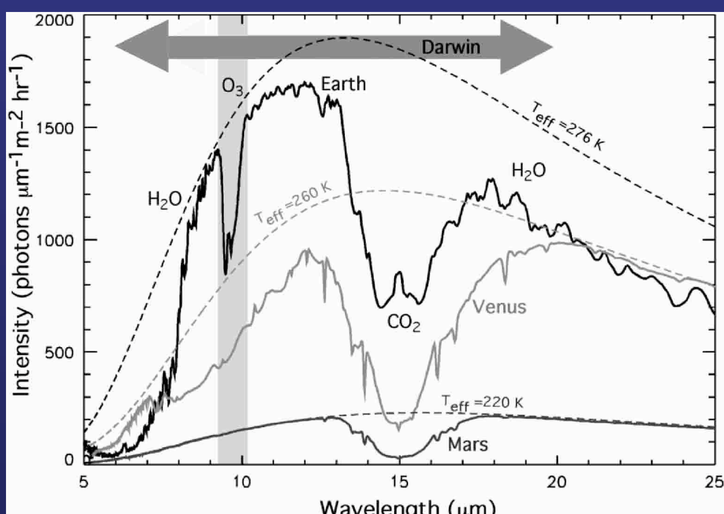
# Detecting Earth-area Planets is Difficult

- Detecting light from planets beyond solar system is hard:
  - Earth sized planet emits few photons/sec/m$^2$ at 10 μm
  - Parent star emits $10^6$ more
  - Planet within 1 AU of star
  - Exozodi dust emission in target solar system ×300 brighter than earth-area planet for equivalent of *ONE* Solar System Zodi



# Earth Spectrum & Other Terrestrial Planets



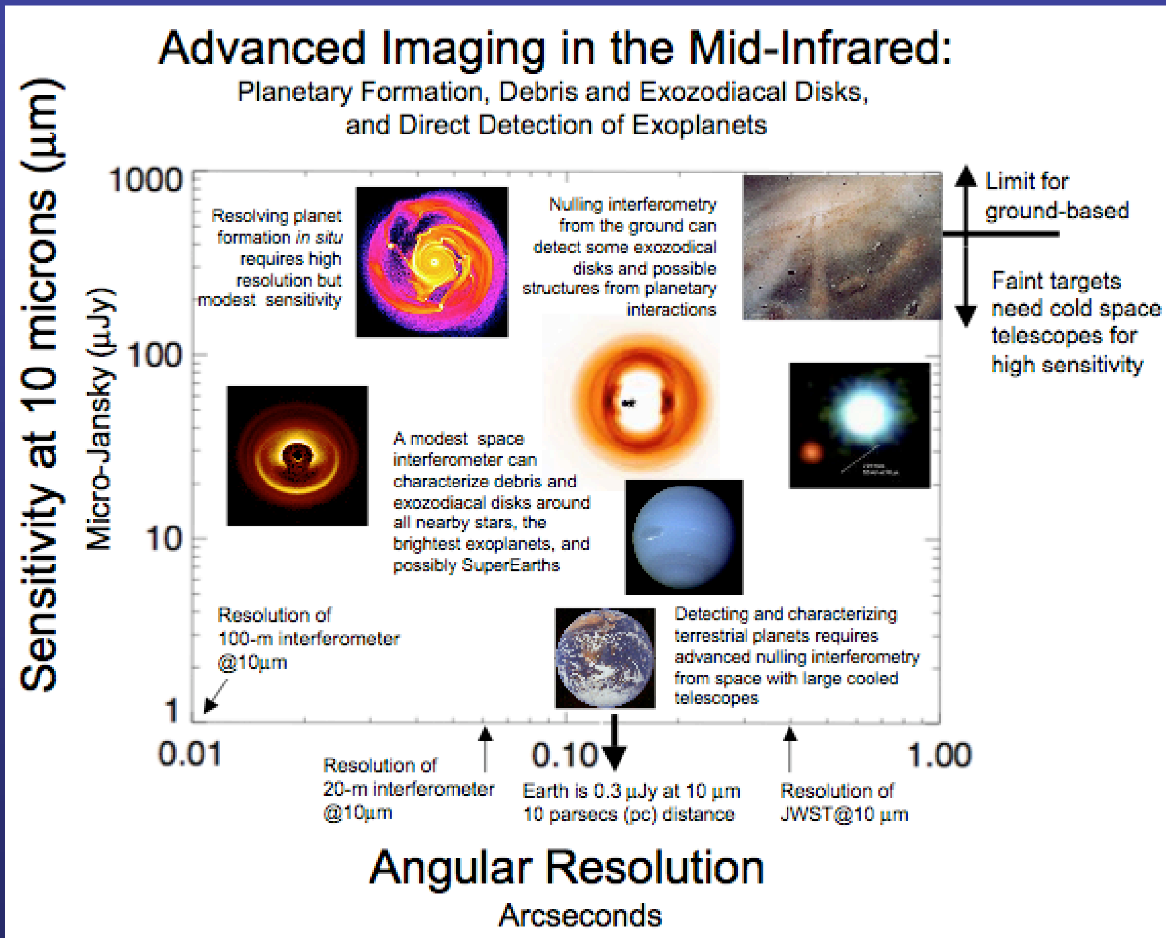




Earth's spectrum shows absorption features from many species, including ozone, nitrous oxide, water vapor, carbon dioxide, and methane

Biosignatures are molecules out of equilibrium such as oxygen, ozone, and methane or nitrous oxide.

Spectroscopy with R~50 is adequate to resolve these features.

# Sensitivity and Resolution in the Mid-IR



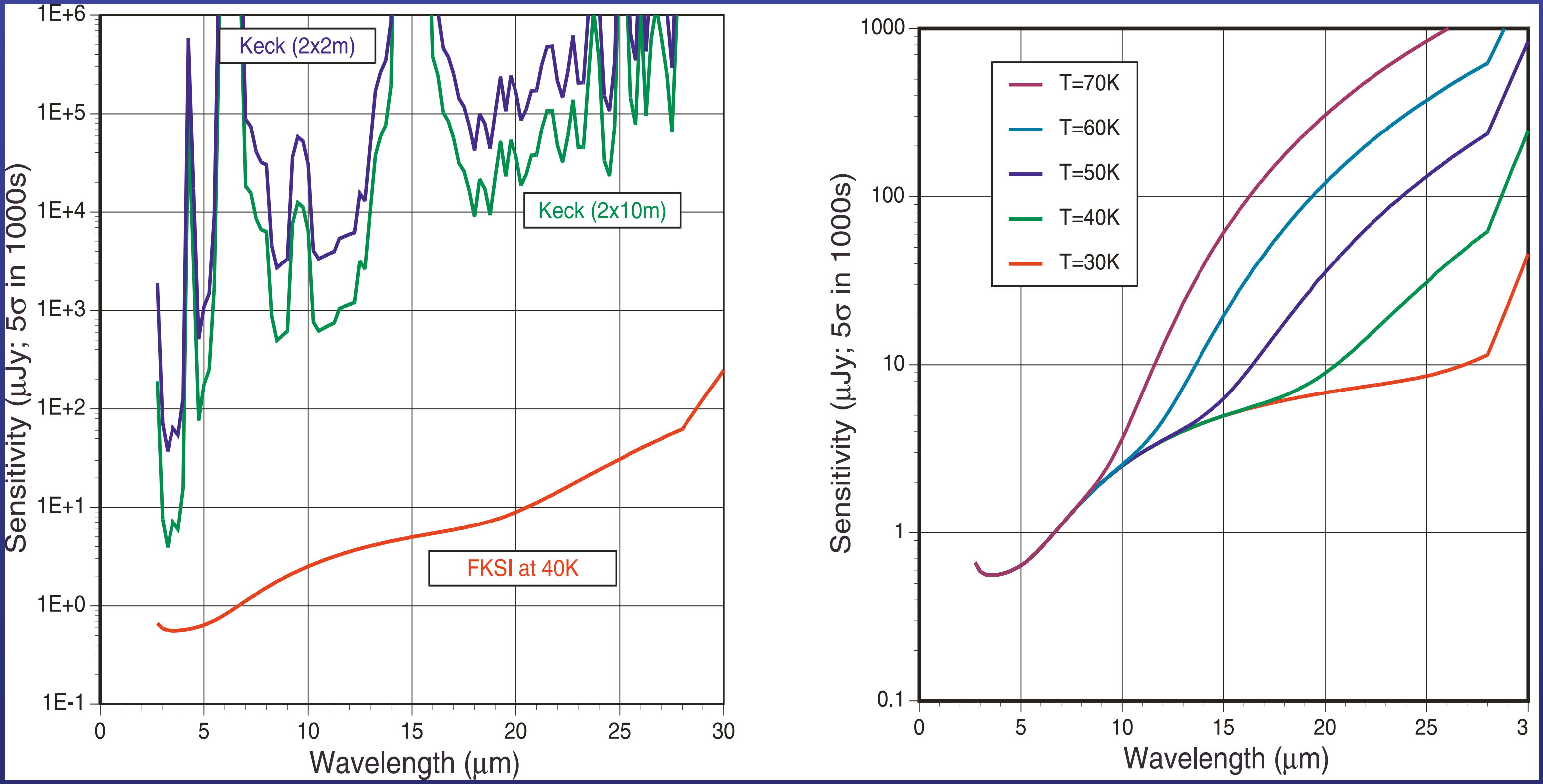

Ground-based interferometry in the IR:

- Limited sensitivity
- Long baselines available
- Good for studying protoplanetary disks

Space-based interferometry:

1. Structurally Connected interferometer (limited baseline length)
   - Exozodi levels for ALL TPF/Darwin stars
   - Debris Disks
   - Characterize Warm & Hot Planets & Super Earths
2. Formation-flying or tethers (long baselines)
   - Detect and characterize many Earth-sized planets
   - Transformational astrophysics

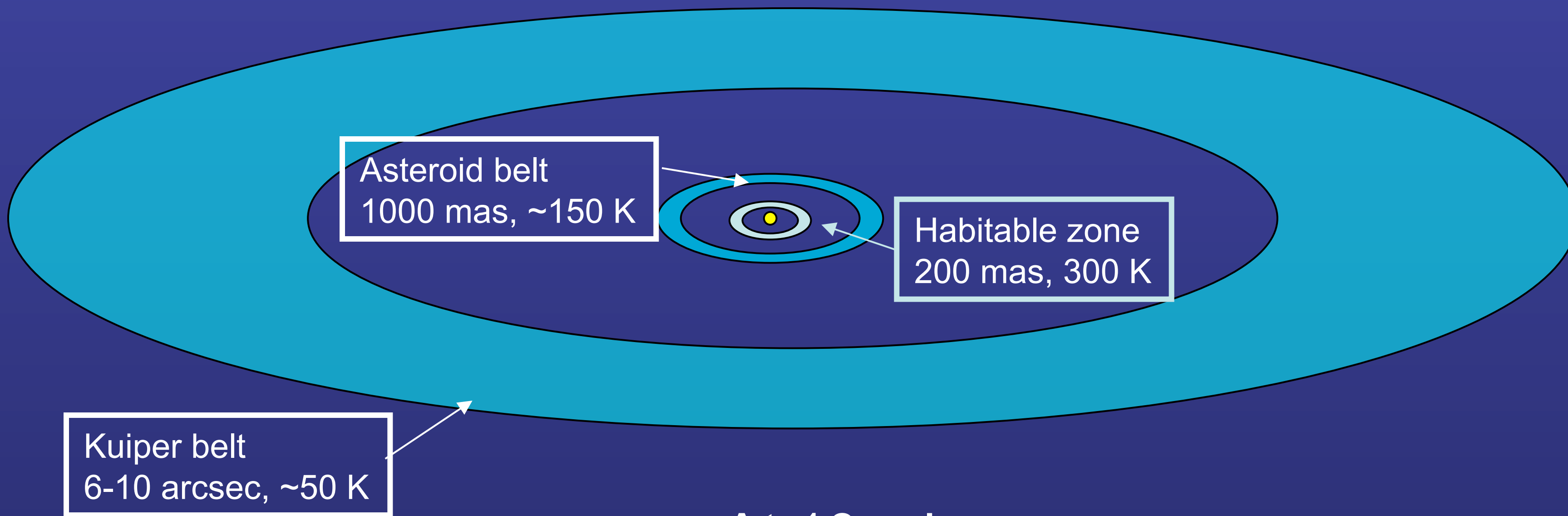
# A SMALL Cooled Space Telescope is Very Sensitive Compared to a LARGE Ground-based Telescope




**Left panel** . The sensitivity of the FKSI system (1 m telescopes) with telescope temperature at 40 K compared to either two 10 m Keck telescopes or two Keck 2 m outrigger telescopes.
**Right panel**. Effect of telescope temperature on FKSI sensitivity.

# Solar System angular size scales

G star at 10 pc (roughly to scale – angular sizes given in diameters)




## At 10 microns:

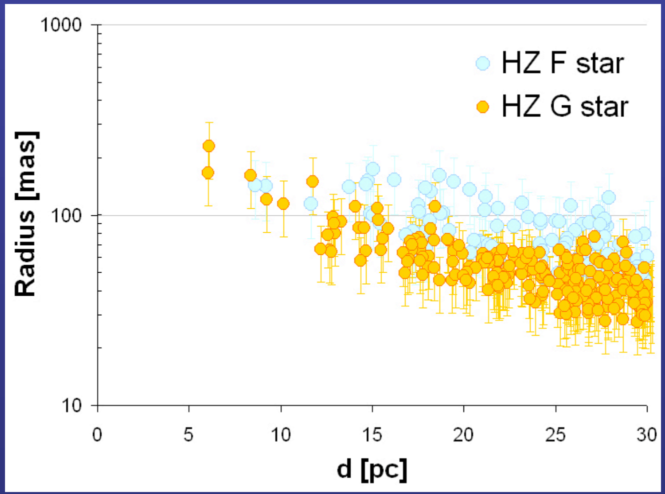
**KI: resolution~ 12 mas**

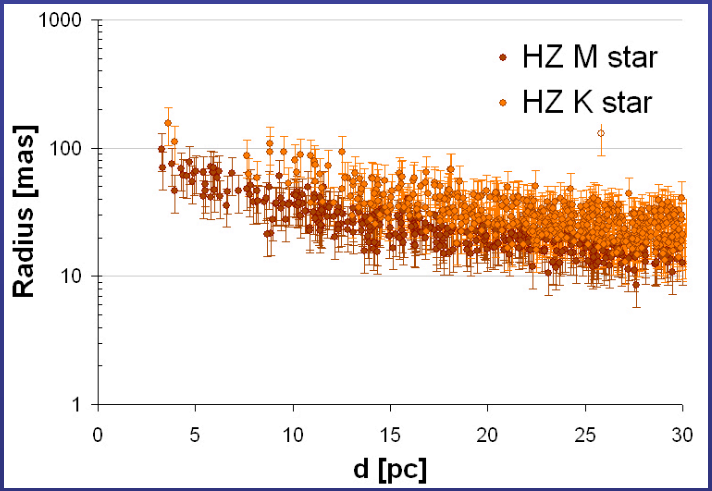
**LBTI: resolution ~ 46 mas**

**JWST: resolution ~ 390 mas**

**Spitzer: resolution ~ 2 arcsec**

# Angular Size of the Habitable Zone

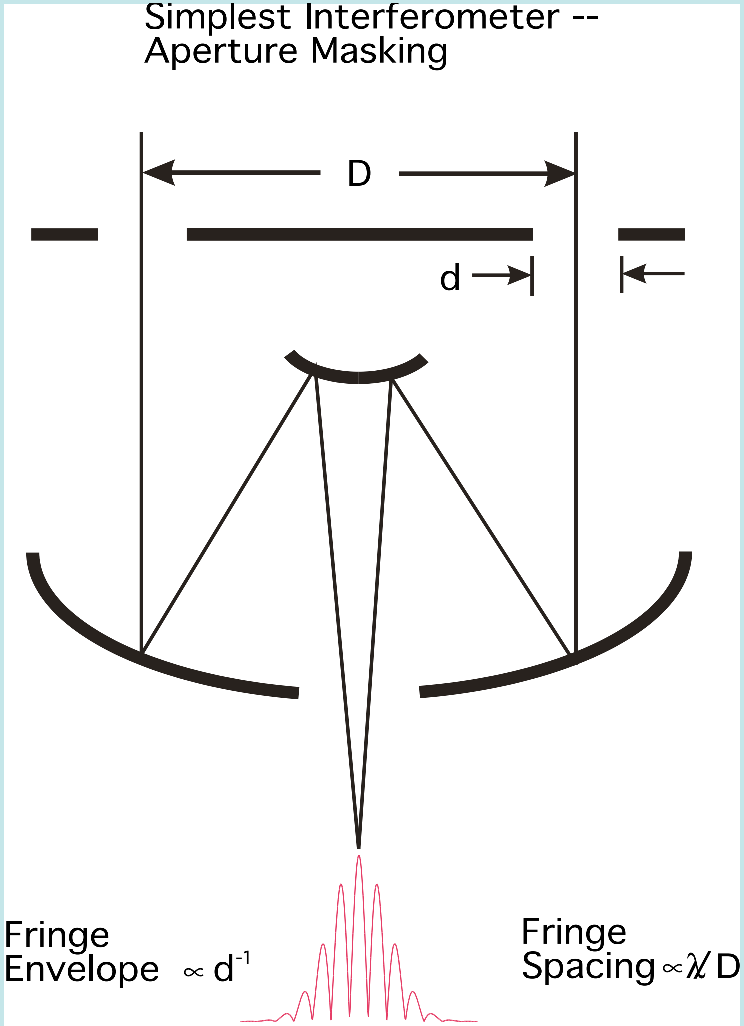


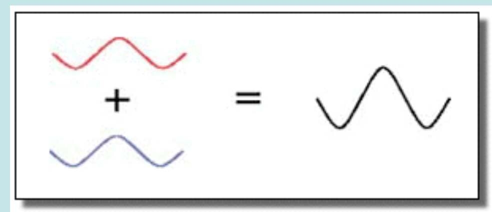

Size of habitable zone is 10 < HZ (mas) < 200

for all F,G,K, M stars < 30 pc from Earth

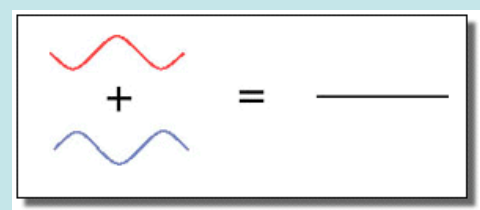
# A simple interferometer



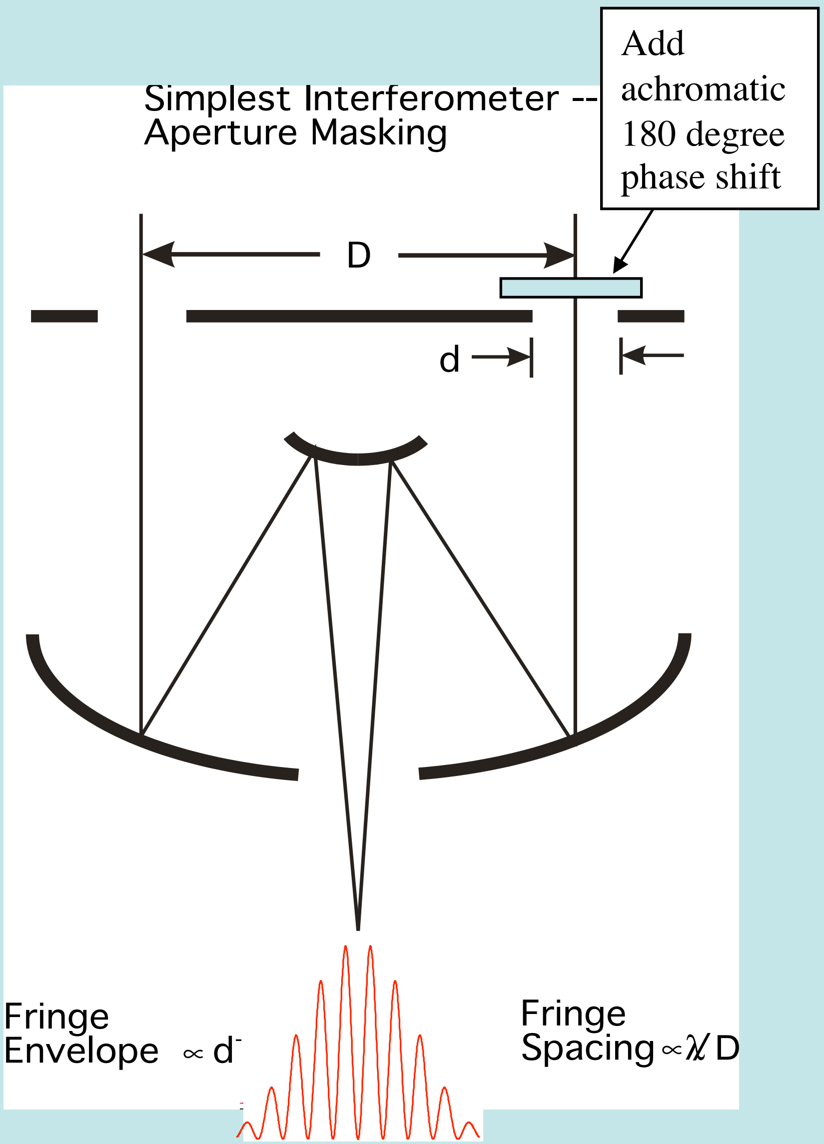

•You get a peak when pathlengths are equal on both sides -- "white light fringe"



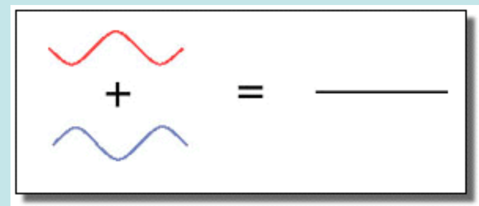

•You get a null when pathlengths differ by one half a wavelength -- a "dark fringe"



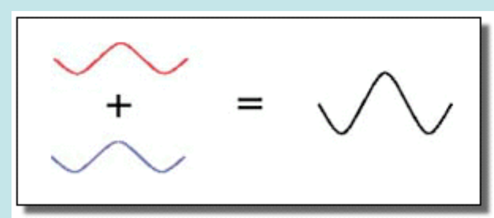
# A simple nulling interferometer




•You get a null when pathlengths are equal on both sides -- “white light null fringe”




•You get a peak when pathlengths differ by one half wavelength -- a “bright fringe”



# Interferometer Resolution
## (Also Inner Working Angle, roughly speaking)

**Interferometer Resolution is:**

$\lambda/(2B)$ where $\lambda$ is wavelength and B is the baseline.

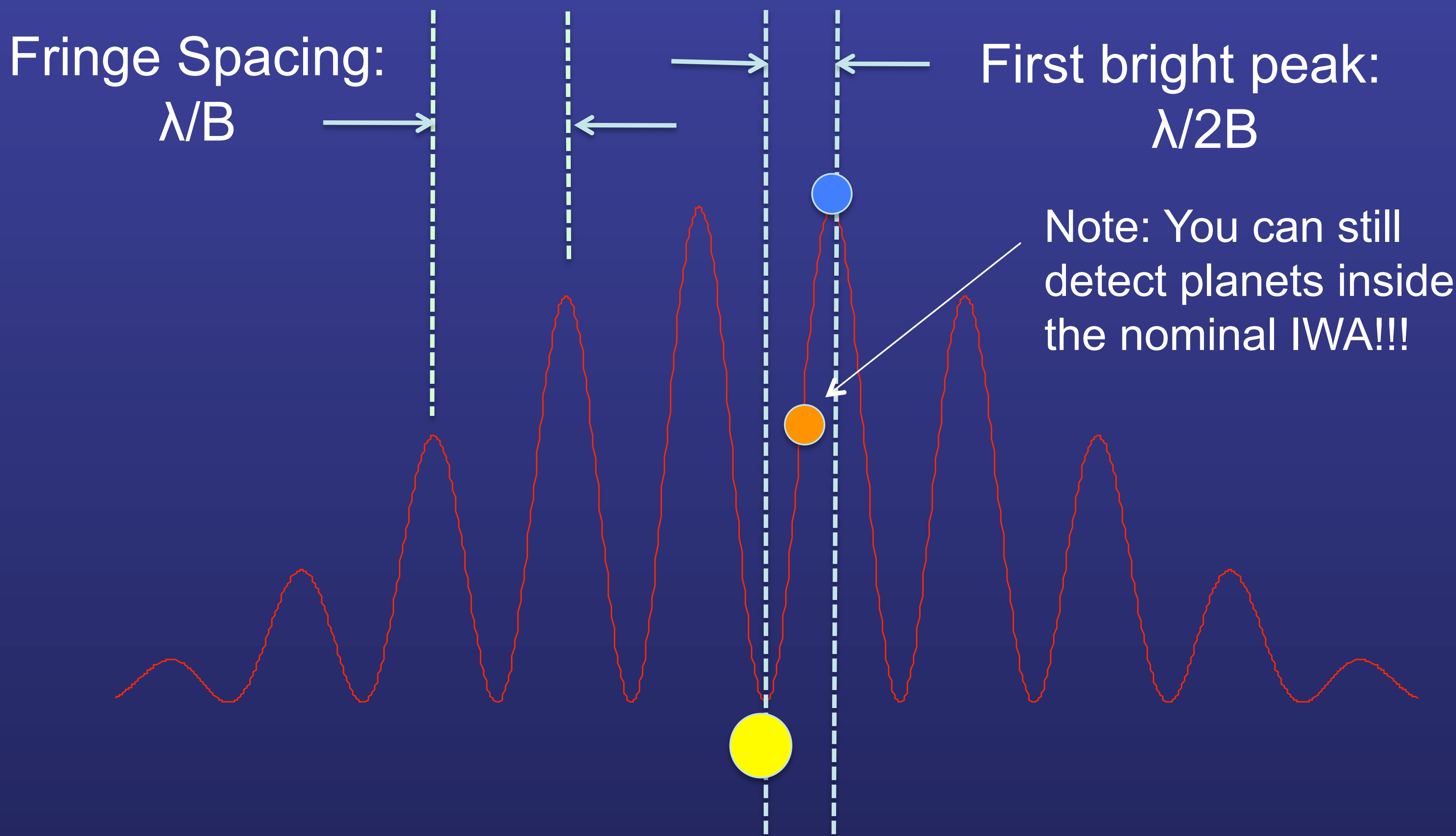
For 100 mas resolution --> B = 10 m at 10 μm

10 mas resolution --> B = 100 m at 10 μm

***This sets the minimum baseline size***.

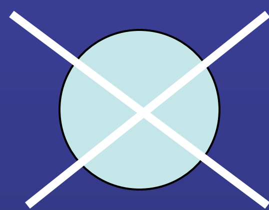
*A 20-40 m baseline at 10 μm is adequate resolution for a substantial number of nearby F,G,K, stars, or 1/2 that if the center wavelength is 5 μm.*

# Inner Working Angle
# (roughly speaking)



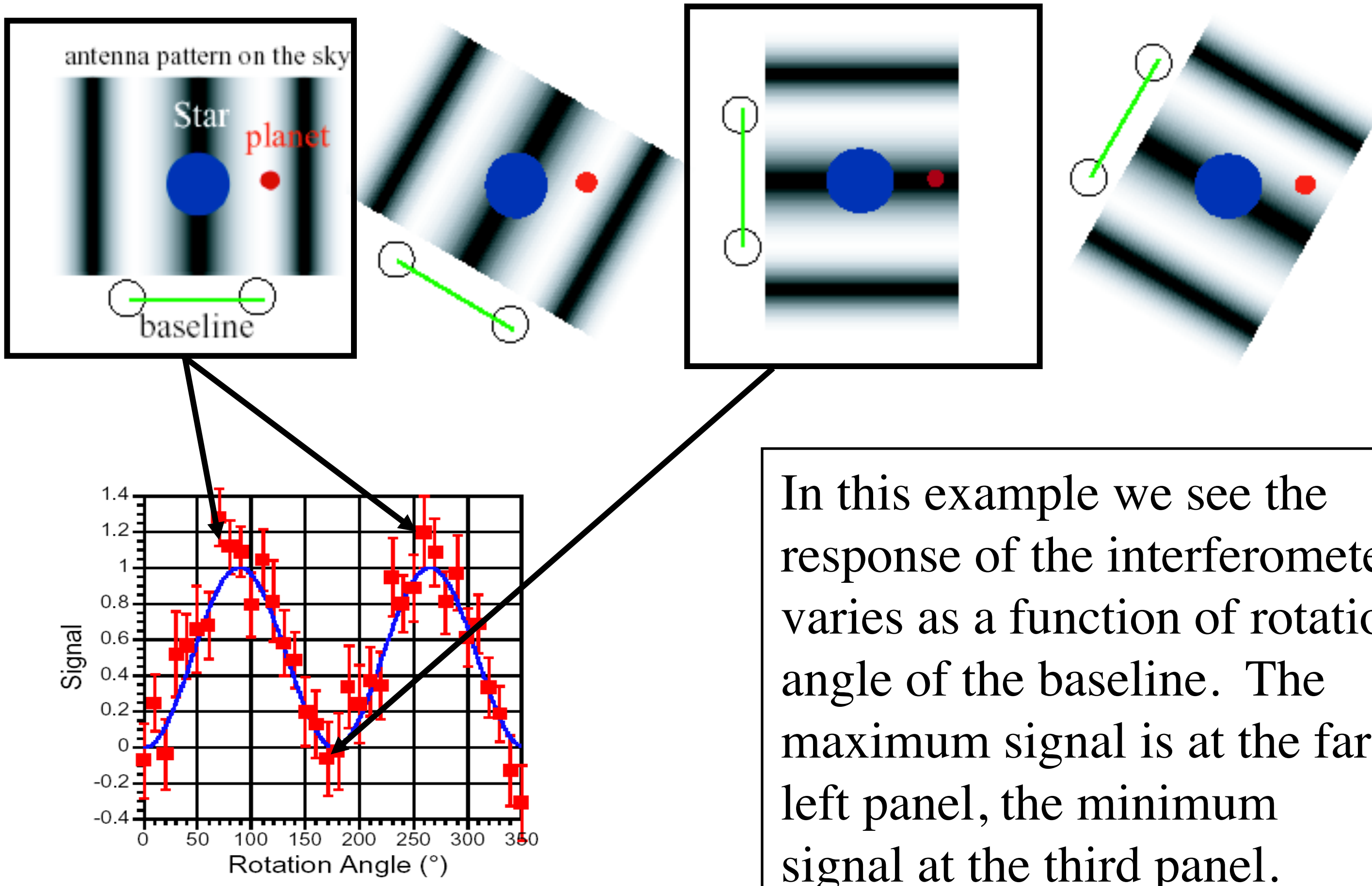
# IWA Discussion

- Thus the IWA is a "soft" function for an interferometer
- It is NOT a circle that blocks all the light for $\theta < \theta_{circle}$



- The response is more complex and subtle, so one must be careful in discussing detectability of planets based on simple IWA arguments.
- Also this is an issue regarding regarding revisit strategies, etc.

# A Simple Example of an Interferometric Detection of a Planet




In this example we see the response of the interferometer varies as a function of rotation angle of the baseline. The maximum signal is at the far left panel, the minimum signal at the third panel.

# Observations and some findings

•*Advanced imaging with both high-angular resolution and high sensitivity in the mid-infrared is essential for future progress across all major fields of astronomy*.

•*Exoplanet studies particularly benefit from these capabilities.*

•*Thermal emission from the atmospheric and telescope(s) limits the sensitivity of ground-based observations, driving most science programs towards space platforms.*

•*Even very modest sized cooled apertures can have orders of magnitude more sensitivity in the thermal infrared than the largest ground-based telescopes currently in operation or planned*.

•*We find a mid-IR interferometer with a nulling capability on the ground and a connected-element space interferometer both enable transformative science while laying the engineering groundwork for a future "Terrestrial Planet Finder" space observatory requiring formation-flying elements*.

# Technology Progress

**The “fundamental physics” experiments have been demonstrated and the guidance, navigation and control problem has been validated**

- Interferometer Milestones established in TPF-I Tech Plan June 2005
  - √ #M1: Intensity & Phase Compensation over 30% bandwidth July 2007
  - √ #M2: Precision Formation Maneuvers with traceability to flight Jan 2008
  - √ #M3: Broadband $10^{-5}$ starlight suppression > 25% bandwidth light Feb 2009*
  - – #M4: Planet detection with chopping and rotation May 2009
  - – #M5: Broadband instability noise suppression Oct 2009

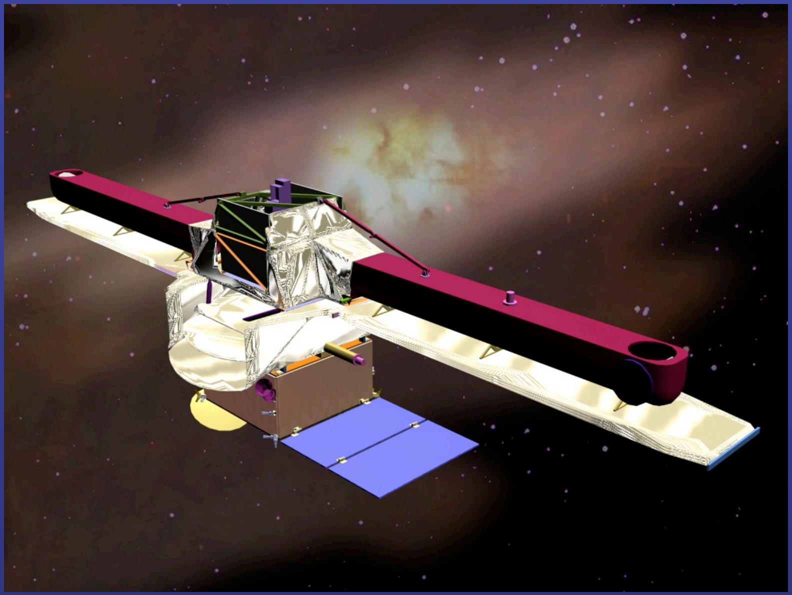
- These demonstrations are equally valid for any mid-IR interferometer concept being considered in the US or in Europe
  - Approach and goals are independent of mission type or size
  - Planet Detection Testbed is the key facility for the demonstration of mid-IR interferometry through TRL 4/5.

**Future efforts will include the following**

- Emphasize modeling and validation demonstrations
- Bring the technology to TRL 6, with testing in vacuum and at cryogenic temperatures where relevant
- Provide path towards flight readiness

*Milestone Review in February 2009

# A Small Structurally Connected Interferometer; The Fourier-Kelvin Stellar Interferometer (FKSI) Mission



PI: Dr. William C. Danchi
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NASA Goddard Space Flight Center

## Technologies:

- Infrared space interferometry
- Large cryogenic infrared optics
- Passive cooling of large optics
- Mid-infrared detectors
- Precision cryo-mechanisms and metrology
- Precision pointing and control
- Active and passive vibration isolation and mitigation

## Key Science Goals

- **Survey of 2 $R_{earth}$ planets around nearby stars**
- **Observe Circumstellar Material**
  - Exozodi measurements of nearby stars and search for companions
  - Debris disks, looking for clumpiness due to planets
- **Characterize Known Extra-solar Planets**
  - Characterize atmospheres with R=20 spectroscopy
  - Observe secular changes in spectrum
  - Observe orbit of the planet
  - Estimate density of planet, determine if rocky or gaseous
  - Determine main constituents of atmospheres
- **Star formation**
  - Evolution of circumstellar disks, morphology, gaps, rings
- **Extragalactic astronomy**
  - AGN nuclei

## Key Features of Design:

- ~0.5 m diameter aperture telescopes
- Passively cooled (<70K)
- 12.5 m baseline
- 3 – 8 (or 10 TBR) micron science band
- 0.6-2 micron band for precision fringe and angle tracking
- Null depth better than 10^-4 (floor), 10^-5 (goal)
- R=20 spectroscopy on nulled and bright outputs of science beam combiner

# Findings Concerning the Performance of a Small Structurally Connected Interferometer

*•To date, progress has been made on the physical characteristics of planets largely through transiting systems, but a small planet finding interferometer can measure the emission spectra of a large number of the non-transiting ones, as well as more precise spectra of the transiting ones.*

*•As a conservative estimate, we expect that a small system could detect (e.g. remove the sin(i) ambiguity) and characterize about 75-100 known exoplanets.*

*•A small mission is ideal for the detection and characterization of exozodiacal and debris disks around ALL TPF candidate stars in the Solar neighborhood*

*•If the telescopes are somewhat larger than has been discussed in some of the existing mission concepts (e.g., 1-2 m) and are somewhat cooler (e.g., < 60K) so that the system can operate at longer wavelengths, it is possible for a small infrared structurally-connected interferometer to detect and characterize super-earths and even ~50-75 earth-sized planets around the nearest stars.*

***•Further studies of the capabilities of a small infrared structurally-connected interferometer are necessary to improve upon our estimates of system performance***

# Flagship Mission Requirement Summary

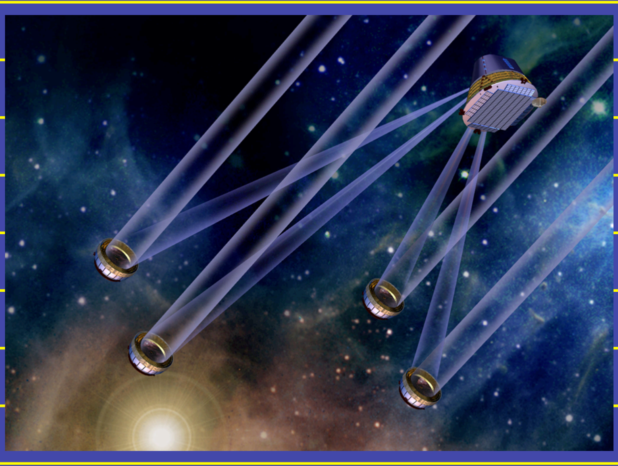
| Flagship Interferometer Mission Requirement Summary | |
|---|---|
| **Star Types** | F, G, K, selected, nearby M, and others |
| **Habitable Zone** | 0.7–1.5 (1.8) AU scaled as $L^{1/2}$ *(Note *)* |
| **Number of Stars to Search** | >150 |
| **Completeness for Each Core Star** | 90% |
| **Minimum Number of Visits per Target** | 3 |
| **Minimum Planet Size** | 0.5–1.0 Earth Area |
| **Geometric Albedo** | Earth's |
| **Spectral Range and Resolution** | 6.5–18 [20] μm; R = 25 [50] |
| **Characterization Completeness** | Spectra of 50% of Detected or 10 Planets Maximum |
| **Giant Planets** | Jupiter Flux, 5 AU, 50% of Stars |
| **Maximum Tolerable Exozodiacal Emission** | 10 times Solar System Zodiacal Cloud |

*There are two definitions in the literature for the outer limit of the habitable zone. The first is 1.5 AU scaled to the luminosity to the ½ power based on Kasting et al. (1993). The second is 1.8 AU scaled in the same way from Forget & Pierrehumbert (1997).

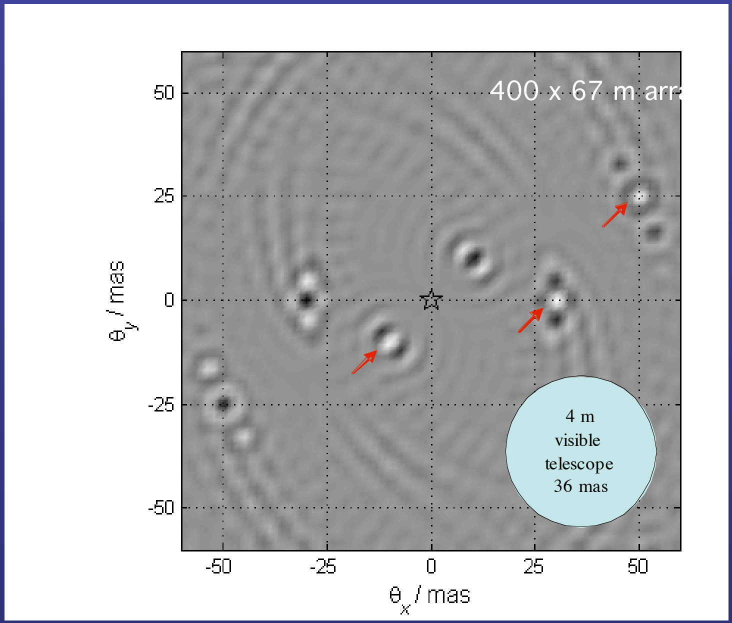
# Properties of a Flagship Mid-IR Observatory

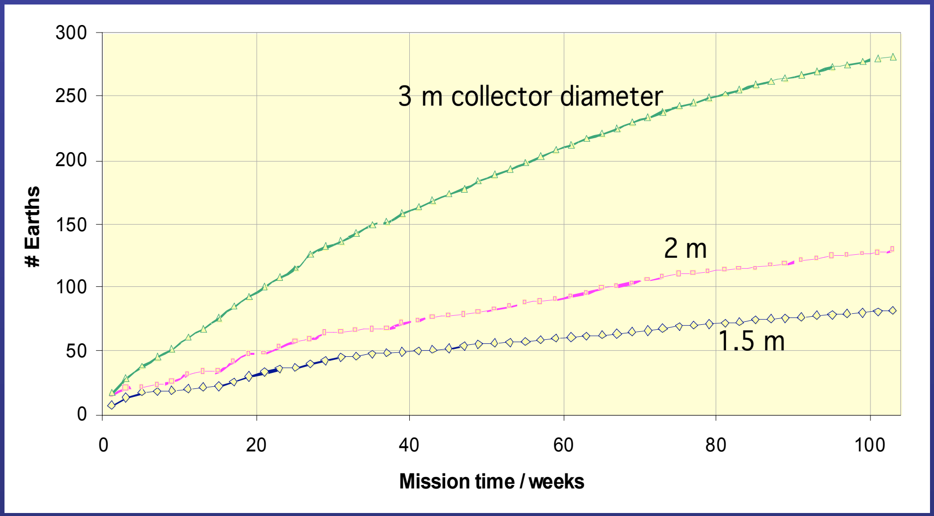
## Illustrative Properties of a Flagship Mid-IR Observatory Concept

| **Parameter** | **4-Telescope Chopped X-Array Emma Design** |
|---|---|
| **Collectors** | Four 2-m diameter spherical mirrors, diffraction limited at 2 µm operating at 50 K |
| **Array shape** | 6:1 rectangular array |
| **Array size** | 400 × 67 m to 120 × 20 m |
| **Wavelength range** | 6–20 µm |
| **Inner working angle** | 13–43 mas (at 10 mm, scaling with array size) |
| **Angular resolution** | 2.4 mas to 8.2 mas (at 10 µm, scaling with array size) |
| **Field-of-view** | 1 arcsec at 10 µm |
| **Null depth** | $10^{-5}$ at 10 mm (not including stellar size leakage) |
| **Spectral resolution $\Delta\lambda/\lambda$** | 25 (for planets); 100 for general astrophysics |
| **Sensitivity** | 0.3 µJy at 12 µm in 14 hours (5s) |
| **Target Stars** | 153 (F, G, K, and M main-sequence stars) |
| **Detectable Earths** | 130 (2 year mission time, 1 Earth per star) |
| **Exozodiacal emission** | Less than 10 times our solar system |
| **Biomarkers** | $CO_2$, $O_3$ , $H_2O$, $CH_4$ |
| **Field of regard** | Instantaneous 45˚ to 85˚ from anti-Sun direction, 99.6% of full sky over one year. |
| **Orbit** | L2 Halo orbit |
| **Mission duration** | 5 years baseline with a goal of 10 years |
| **Launch vehicle** | Ariane 5 ECA or equivalent |



# Flagship Mid-IR Performance Summary

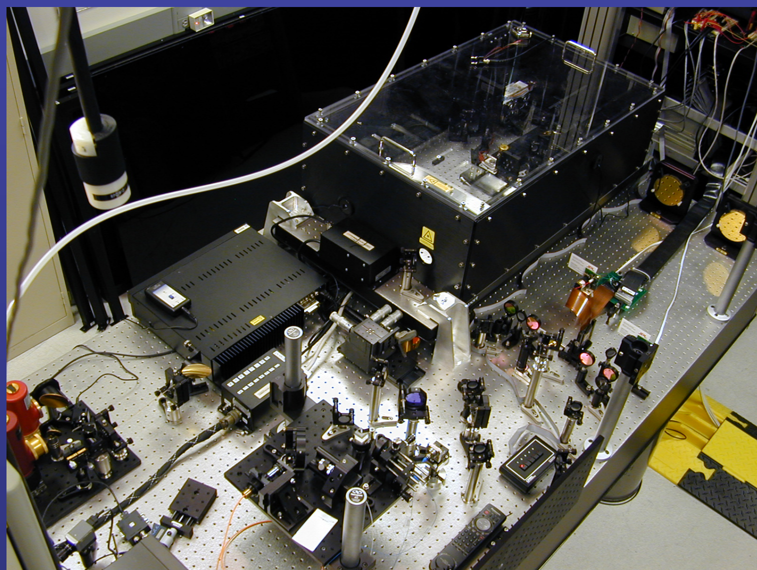


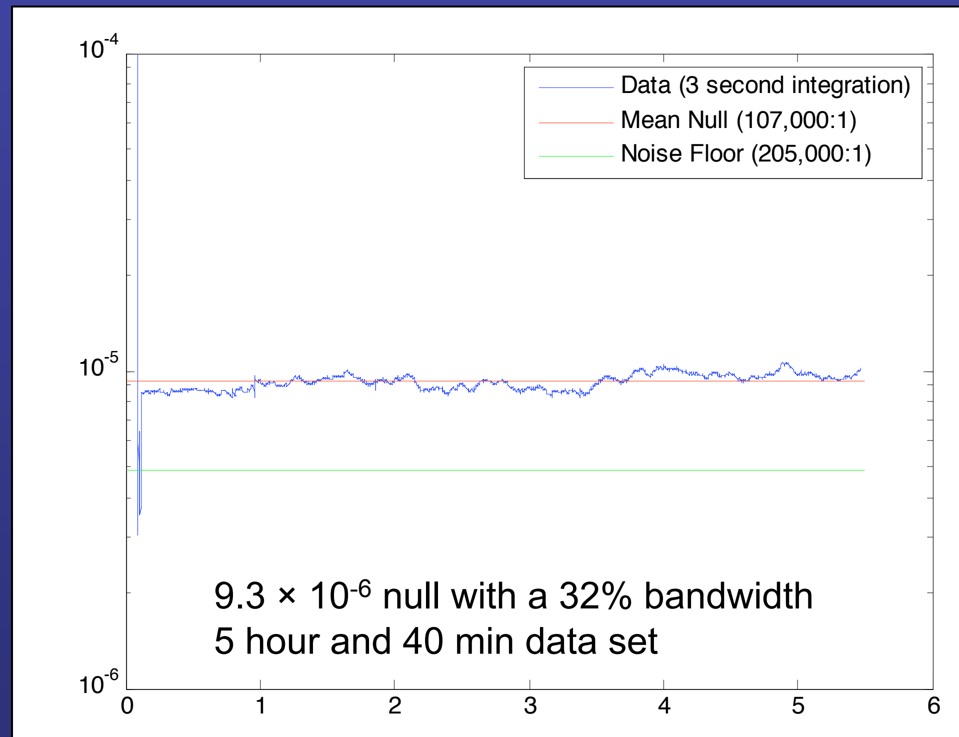




Simulated ‘dirty’ image from Emma X-Array, prior to deconvolution. Angular resolution is 2.5 mas. Planet locations are indicated by red arrows.

Predicted number of Earths detectable by Emma X-Array architecture as a function of elapsed mission time and collector diameter

# Milestone #1: Phase & Amplitude Control
# Milestone #3: Broadband Nulling





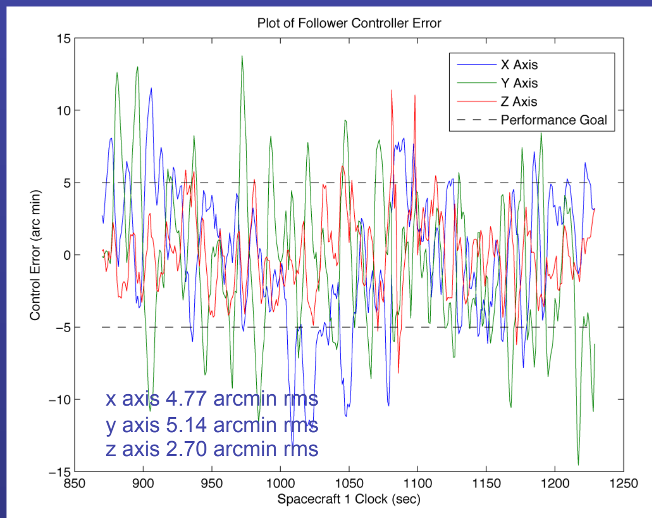

**Goal:** Mid-infrared nulling with mean null depth of $1 \times 10^{-5}$ using a 25% bandwidth centered at 10 microns; three 6-hour experiments. (Whitepaper signed, 10 October 2007)

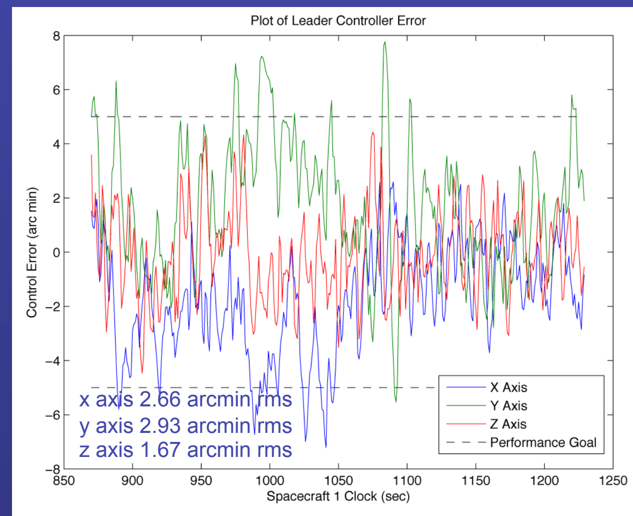
***World record broadband mid-IR null, exceeds flight requirements***

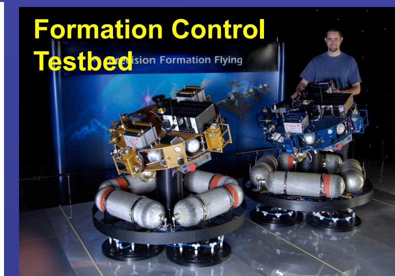
Rejection Ratio
161339 :1

- Intensity imballance
  0.11 %
- Phase Dispersion
  4.8 nm
- Path Control
  3.54 nm
- Birefringence
  0 nm
- Pupil Rotation
  0 deg
- Noise Floor
  4.89E-06 V_norm

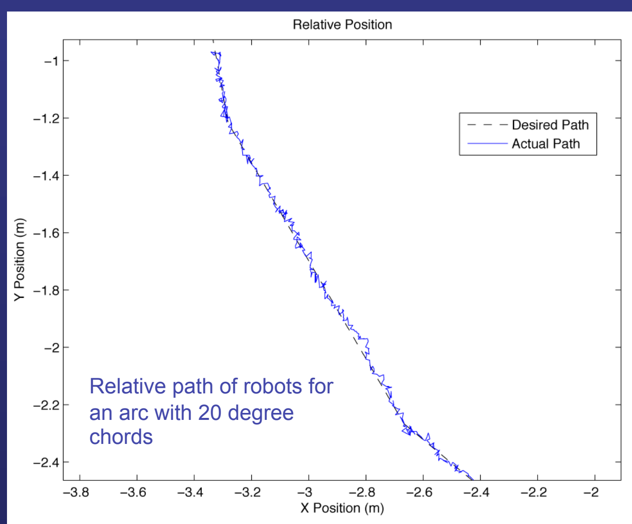
# Milestone #2: Formation Control

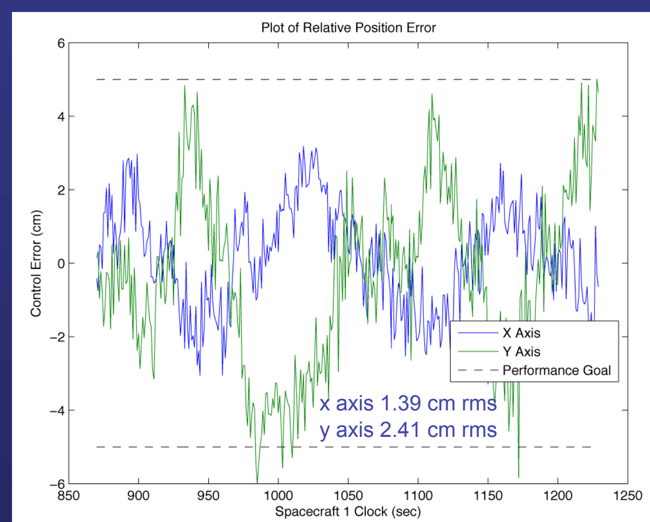



**TPF-I Milestone #2** experiments for the formation precision performance maneuver were completed 30 September 2007




Goal:

Per axis translation control < 5 cm rms

Per axis rotation control < 6.7 arcmin rms

Demonstrated with arcs having 20 and 40 degree chords. Experiments repeated three times, spaced at least two days apart.

Milestone Report published 16 January 2008

Example Milestone Data: Rotation maneuver with 20 degree chord segments

# Planet Detection Testbed

**Will conclude the room-temperature nulling demonstrations for a mid-IR mission**

- Brings the technology to TRL 5 with two system-level demonstrations: Milestone #4 and Milestone #5

- 2009/March: Milestone #4 Report Review
- 2009/June : Milestone #5 Whitepaper Review

**Milestone #4:**
Laboratory demonstration of planet signal extraction with chopping, array rotation, and averaging
(Whitepaper signed, 6 May 2008)

**Milestone #5:**
Laboratory demonstration of planet signal extraction with spectral filtering and instability noise suppression.
(Whitepaper June 2009)

**Additional demonstrations beyond this work would require vacuum cryogenic testing**

- Component (e.g., spatial filters, DMs)
- Subsystem (e.g., adaptive nuller, delay lines)
- System (4-beam broadband with flight-like mechanisms and servos)

# Path toward a Mid-IR Flagship Mission

**The activities required to bring the technology up to TRL 6 may include the following:**

**In-space Demonstrations of Formation Flying (TRL 6)**

- Subsystem Testing
  - RF metrology
  - Optical metrology
- System testing
  - Precision maneuvers
  - Fault tolerant algorithms
  - Collision avoidance demonstrations
  - Fringe tracking with starlight from independent satellites

**Vacuum Cryogenic Engineering of Mid-IR Starlight Suppression (TRL 6)**

- Component (e.g., spatial filters, DMs)
- Subsystem (e.g., adaptive nuller, delay lines, beam combiner)
- System (4-beam broadband with flight-like mechanisms and servos)

# Research & Analysis Recommendations

- ***Ground-based interferometry***
  - *Ground-based interferometry serves critical roles in exoplanet studies. It provides a venue for development and demonstration of precision techniques including high contrast imaging and nulling, it trains the next generation of instrumentalists, and develops a community of scientists expert in their use.*
  - *We endorse the recommendations of the "Future Directions for Interferometry" Workshop and the ReSTAR committee report to continuing vigorous refinement and exploitation of existing interferometric facilities (Keck, NPOI, CHARA and MRO), widening of their accessibility for exoplanet programs, and continued development of interferometry technology and planning for a future advanced facility*
  - *The nature of Antarctic plateau sites, intermediate between ground and space in potential, offers significant opportunities for exoplanet and exozodi studies by interferometry and coronagraphy.*
- ***Space-based Interferometry***
  - *Space-based interferometry serves critical roles in exoplanet studies. It provides access to a spectral range that can not be achieved from the ground and can characterize the detected planets in terms of atmospheric composition and effective temperature. Sensitive technology has already been proven for missions like JWST, SIM, and Spitzer, and within NASA's preliminary studies of TPF*

# More Recommendations on R&A Support

- ***Theory support:***
  - *We will require sustained support of strong astrobiology and atmospheric chemistry programs.*
- ***Agency Coordination & Programmatic Strategy***
  - *NASA and NSF goals, makes it an ideal topic for coordination between the agencies, and we urge NASA and NSF staff to leverage this relationship to cover the full breadth of exoplanet science and technology*
- ***International Coordination, Collaboration, & Partnership***
  - *The relationships forged between US and European collaborators should be fostered during the next decade for further studies of small mission and flagship mission concepts. A new letter of agreement is necessary to further future collaborations.*

# Refereed Papers

**Adaptive Nuller**

- "Broadband phase and intensity compensation with a deformable mirror for an interferometric nuller," R. D. Peters, O. P. Lay, and M. Jeganathan, Appl. Opt. 47, 3920-3926 (2008)

**Spatial Filters**

- "Modal filtering for midinfrared nulling interferometry using single mode silver halide fibers," A. Ksendzov, T. Lewi, O. P. Lay, S. R. Martin, R. O. Gappinger, P. R. Lawson, R. D. Peters, S. Shalem, A. Tsun, and A. Katzir, Appl. Opt. 47, 5728-5735 (2008)

- "Characterization of mid-infrared single mode fibers as modal filters," A. Ksendzov, O. Lay, S. Martin, J. S. Sanghera, L. E. Busse, W. H. Kim, P. C. Pureza, V. Q. Nguyen, and I. D. Aggarwal, Appl. Opt. 46, 7957-7962 (2007)

**Achromatic Phase Shifters**

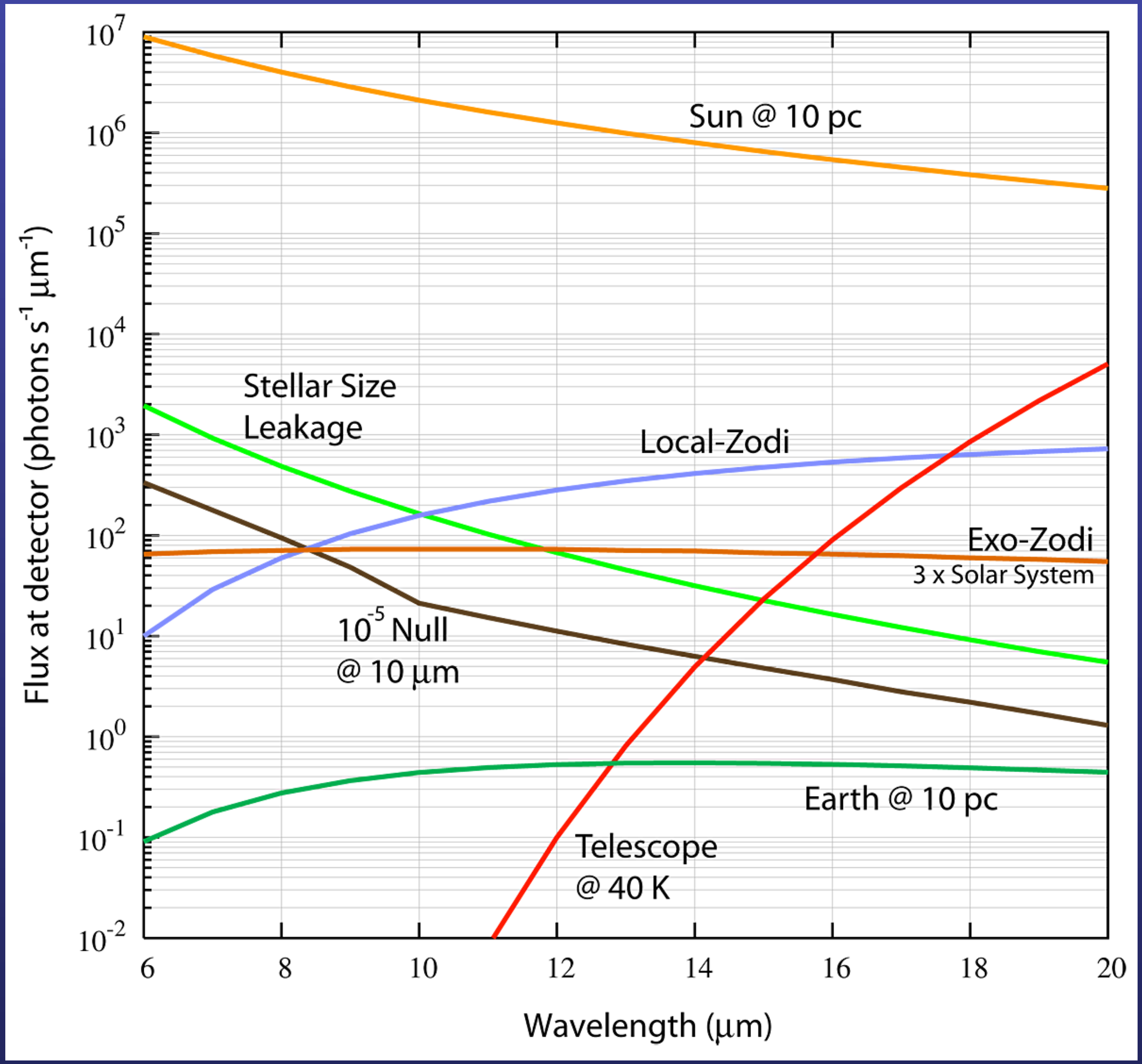
- "Experimental evaluation of achromatic phase shifters for mid-infrared starlight suppression," R. O. Gappinger, R. T. Diaz, A. Ksendvoz, P. R. Lawson, O. P. Lay, K. M. Liewer, F. M. Loya, S. R. Martin, E. Serabyn, and J K. Wallace, Appl. Opt. 48, in press (2009)

**Mid-IR Flagship Mission Concept Paper**

- "Darwin: A mission to detect and search for life on extrasolar planets," C. S. Cockell, A. Léger, M. Fridlund, T. Herbst et al., with contributions from C. Beichman, W. Danchi, K. Johnston, P. Lawson, O. Lay, S. Martin, and E. Serabyn, Astrobiology 9, January (2009)

# Backup Slides

# Sources of Noise

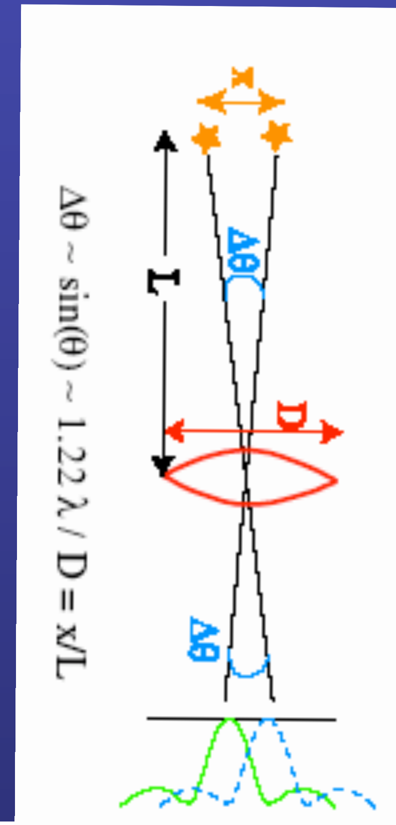


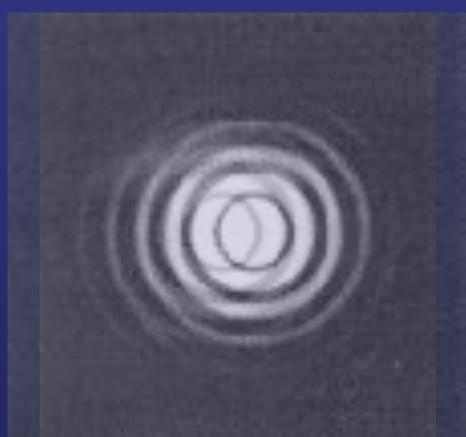
# Resolution of a conventional telescope: Rayleigh Criterion

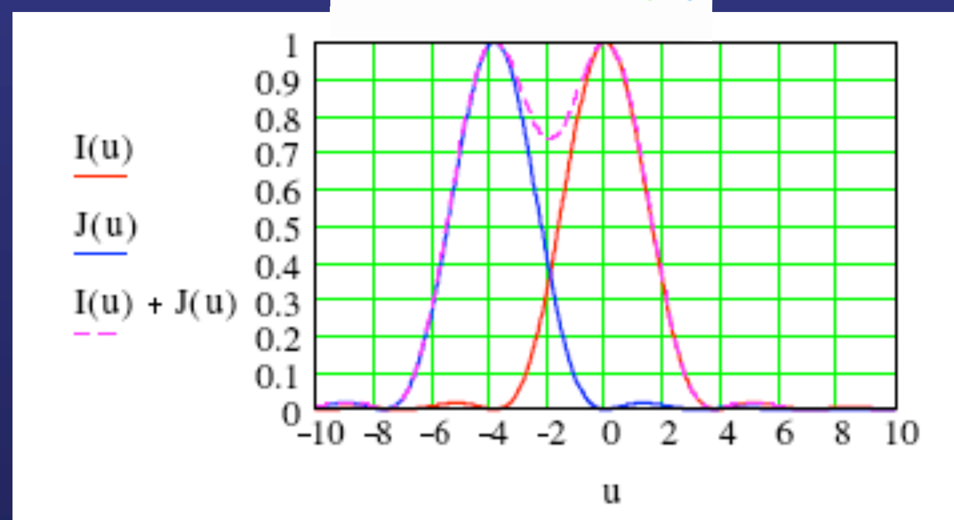
$\theta_{Tel} \sim 1.22\ \lambda\ /\ D$

$\lambda$ = wavelength of light

D = telescope diameter

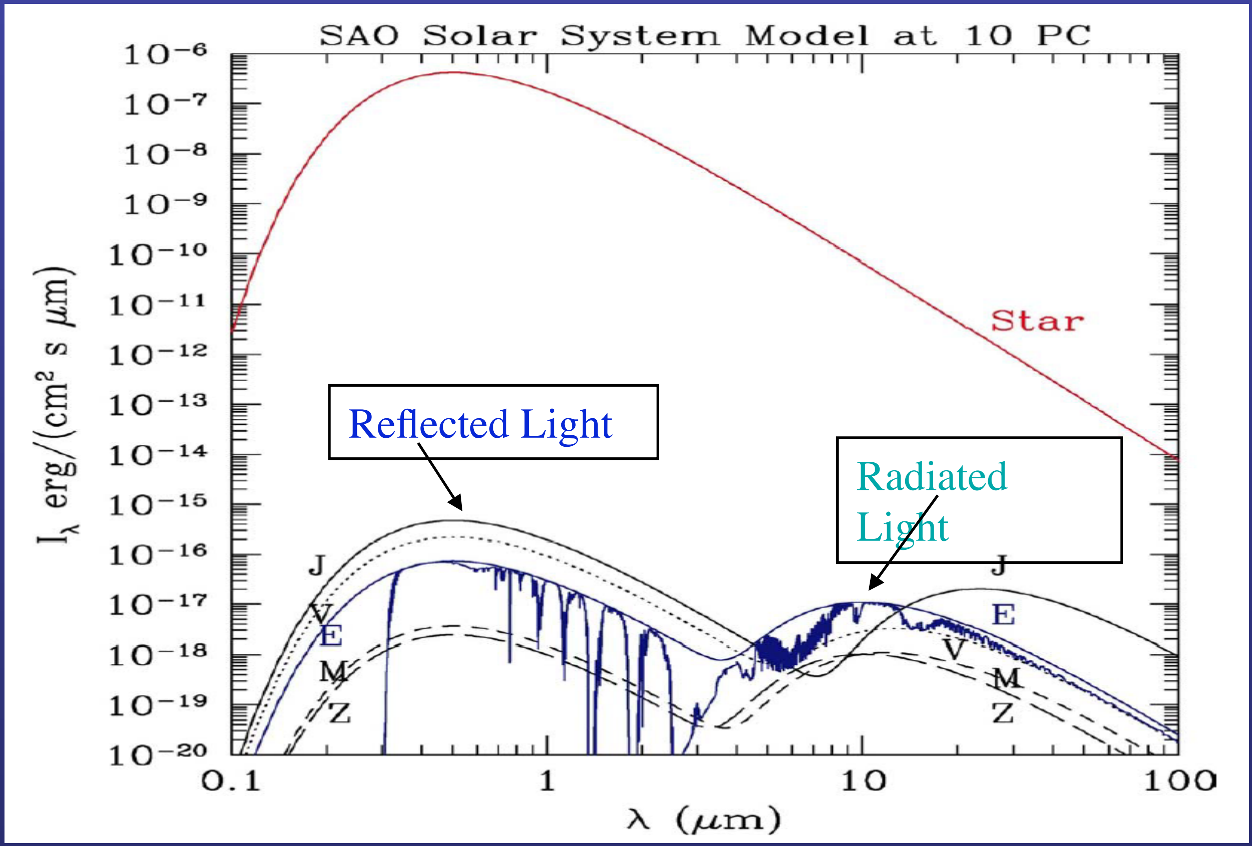




# The Solar System Viewed from 10 pc

You can search for planets directly either from *reflected* starlight or *re-radiated* starlight



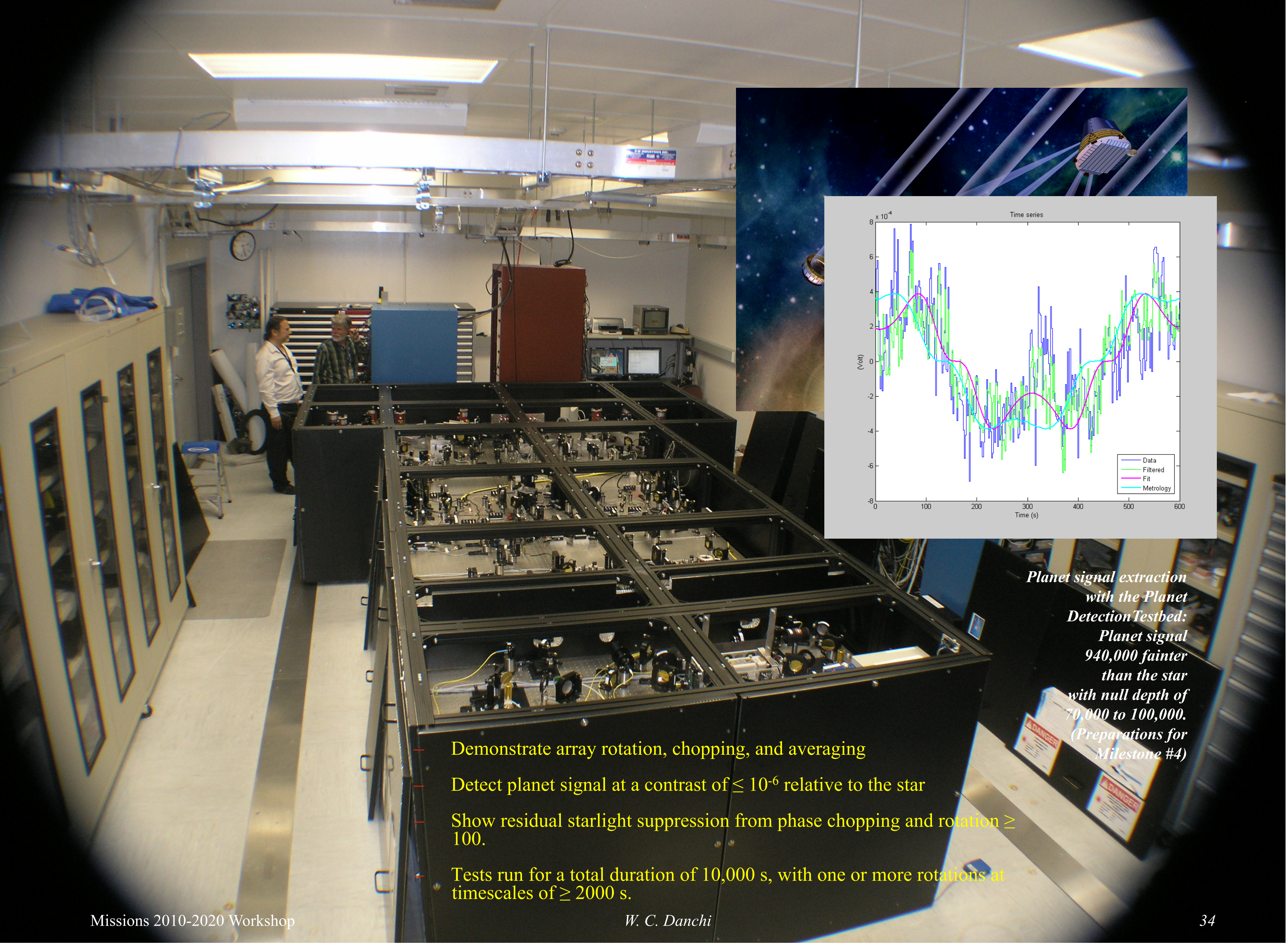

DesMarais et al. (2002)

Notice that *different planets* have *different spectra* in the infrared

# Technical Readiness for a Small Structurally Connected Interferometer

| Item | Description | TRL | Notes |
|---|---|---|---|
| 1 | Cryocoolers | 6 | Source: JWST |
| 2 | Precision cryogenic structure (booms) | 6 | Source: JWST |
| 3 | Detectors (near-infrared) | 6 | Source: HST, JWST Nircam |
| 4 | Detectors (mid-infrared) | 6 | Source: Spitzer IRAC, JWST MIRI |
| 5 | Cryogenic mirrors | 6 | Source: JWST |
| 6 | Optical fiber for mid-infrared | 4 | Source: TPF-I |
| 7 | Sunshade | 6 | Source: JWST |
| 8 | Nuller Instrument | 5 | Source: Keck Interferometer Nuller, TPF-I project, LBTI |
| 9 | Precision cryogenic delay line | 6 | Source: ESA Darwin |

*Note: The requirement for the FKSI project is a null depth of $10^{-4}$ in a 10% bandwidth. Laboratory results with the TPF-I testbeds have exceeded this requirement by an order of magnitude (Lawson et al. 2008).




*Planet signal extraction with the Planet Detection Testbed: Planet signal 940,000 fainter than the star with null depth of 70,000 to 100,000. (Preparations for Milestone #4)*

- Demonstrate array rotation, chopping, and averaging
- Detect planet signal at a contrast of $\leq 10^{-6}$ relative to the star
- Show residual starlight suppression from phase chopping and rotation $\geq$ 100.
- Tests run for a total duration of 10,000 s, with one or more rotations at timescales of $\geq$ 2000 s.

# Some Conclusions

# Ground-based interferometry

## Keck Interferometer

- Protoplanetary disk studies (T Tauri & Herbig Ae/Be stars)
- Debris Disks Around Nearby Stars (Key Science Projects) with limits around 100-200 Solar System Zodis

## Large Binocular Telescope Interferometer

- Debris Disks with lower limits ~30 Solar System Zodis

*These projects have been essential to the development of the nulling technique and they will produce important near-term results.*

# Technology Development for the Large Mission

- Some additional work needs to be done on the warm testbeds to get to $10^{-5}$ null depth requirement, but we are quite close (about 20% above the requirement).
- Cryogenic testing of optical fibers
- Formation flying demonstrations in space

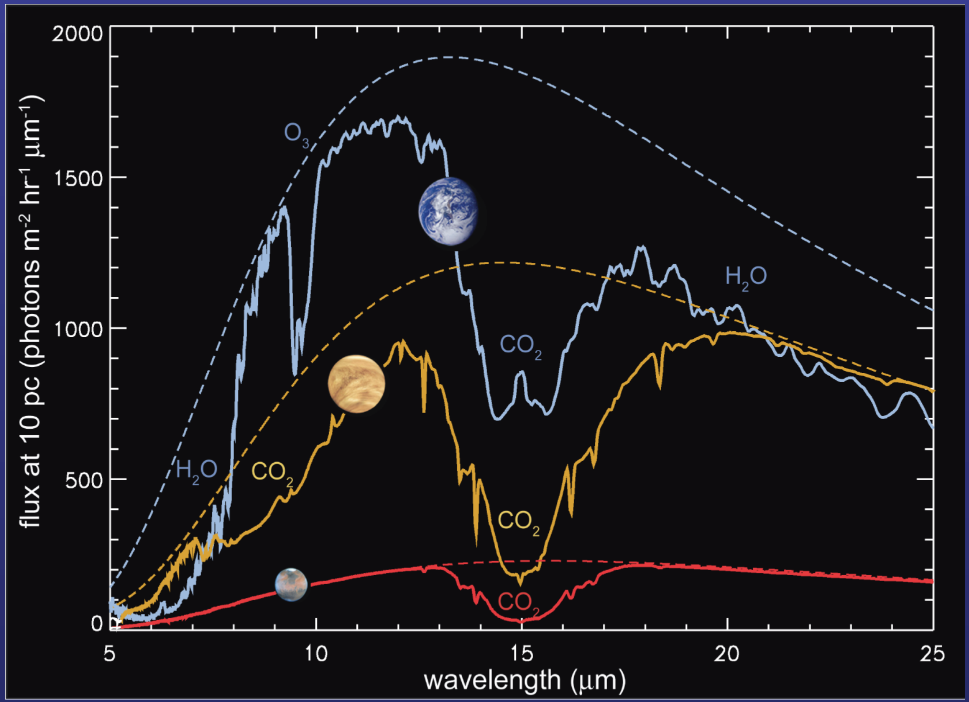
# TPF Interferometer Technology

Peter R. Lawson

January 5, 2009

# Technology for a Mid-IR Interferometer

- Science Requirements
- Architecture trade studies

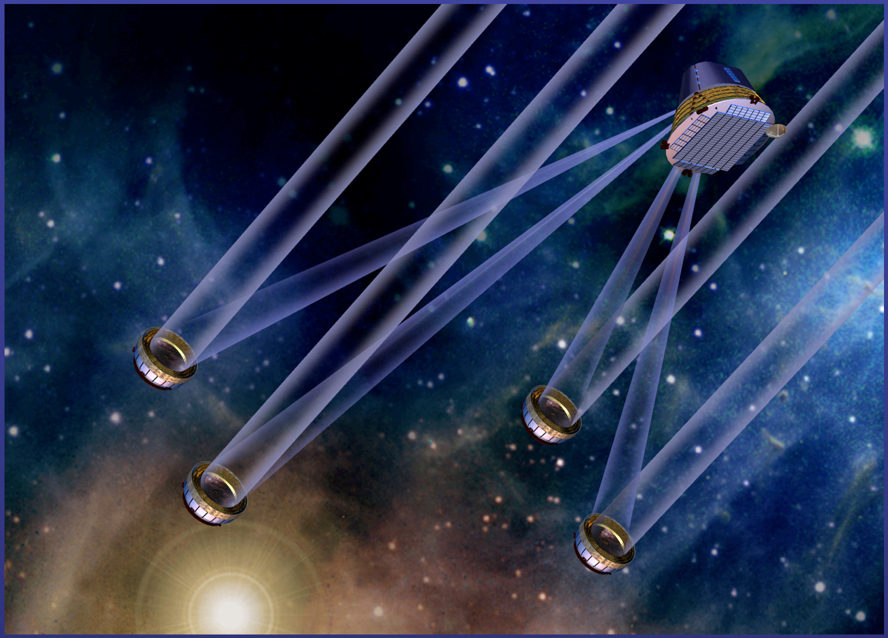



- Starlight suppression
  - Null depth & bandwidth
  - Null stability
- Formation flying
  - Formation control
  - Formation sensing
  - Propulsion systems
- Cryogenic systems
  - Active components
  - Cryogenic structures
  - Passive cooling
  - Cryocoolers
- Integrated Modeling
  - Model validation and testbeds

# Terrestrial Planet Finder Interferometer

**Salient Features**

- Formation Flying Mid-IR nulling Interferometer
- Starlight suppression to and $10^{-5}$ (mid-IR)
- Heavy launch vehicles
- L2 baseline orbit
- 5 year mission life (10 year goal)
- Potential collaboration with European Space Agency



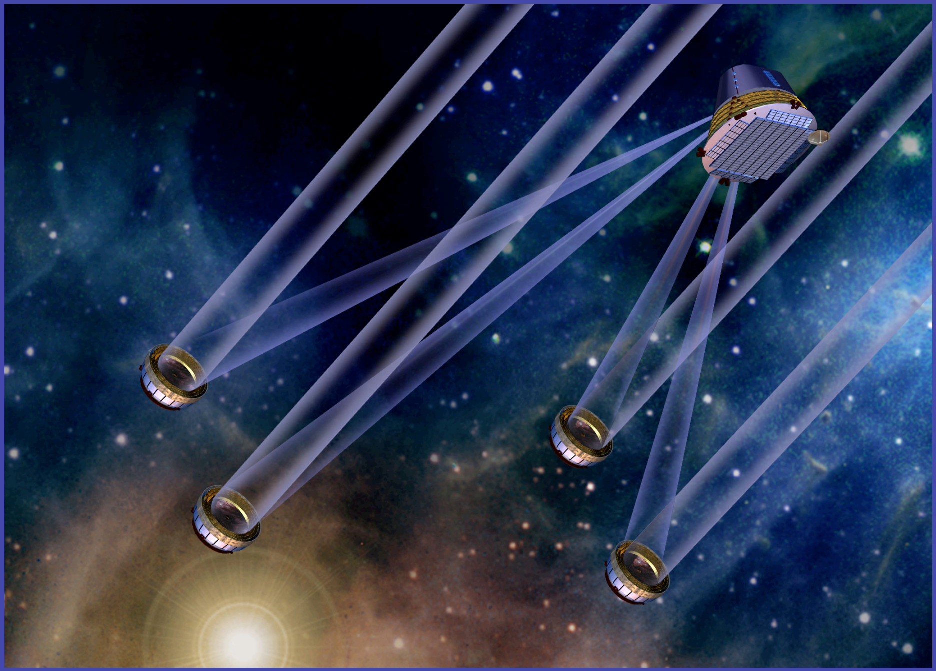
**Science Goals**

- Detect as many as possible Earth-like planets in the "habitable zone" of nearby stars via their reflected light or thermal emission
- Characterize physical properties of detected Earth-like planets (size, orbital parameters, albedo, presence of atmosphere) and make low resolution spectral observations looking for evidence of a *habitable* planet and bio-markers such as $O_2$, $O_3$, $CO_2$, $CH_4$ and $H_2O$
- Detect and characterize the components of nearby planetary systems including disks, terrestrial planets, giant planets and multiple planet systems
- Perform general astrophysics investigations as capability and time permit

# Terrestrial Planet Finder Interferometer

## Salient Features

- Formation flying mid-IR nulling Interferometer
- Starlight suppression to $10^{-5}$
- Heavy launch vehicle
- L2 baseline orbit
- 5 year mission life (10 year goal)
- Potential collaboration with European Space Agency



## Science Goals

- Detect as many as possible Earth-like planets in the habitable zone of nearby stars via their thermal emission
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- Perform general astrophysics investigations as capability and time permit

# Technology Accomplishments and Plans

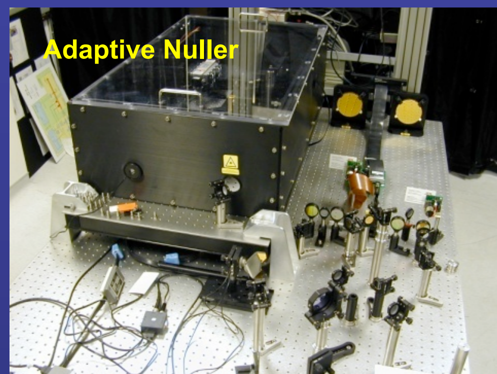
Mid-IR laser and broadband nulling results have exceeded flight requirements.

## Accomplished Milestones

**Milestone #1:** Phase compensation better than 5 nm RMS, with intensity compensation better than 0.2% was demonstrated with the Adaptive Nuller. (24 July 2007)

**Milestone #2:** Guidance navigation and control algorithms for a formation of two telescopes were demonstrated with traceability to flight in a ground-based robotic testbed.
(16 January 2008)

**Milestone #3:** Mid-infrared nulling of < $10^{-5}$ over a 25% bandwidth (32%) were demonstrated with three 6-hour experiments using the Adaptive Nuller. (Pending review February 2009)



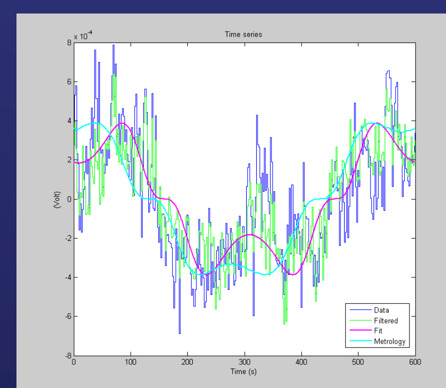

*"TPF-I Milestone #1 Report: Amplitude and Phase Control Demonstration," Edited by R.D. Peters, P.R. Lawson, and O.P. Lay*
*JPL Document 3839, 24 July 24 2007*


*"TPF-I Technology Milestone #2 Report: Formation Control Performance Demonstration,"*
*Edited by D.P. Scharf and P.R. Lawson*
*JPL Document 43009, 16 January 2008*

## Future Milestones

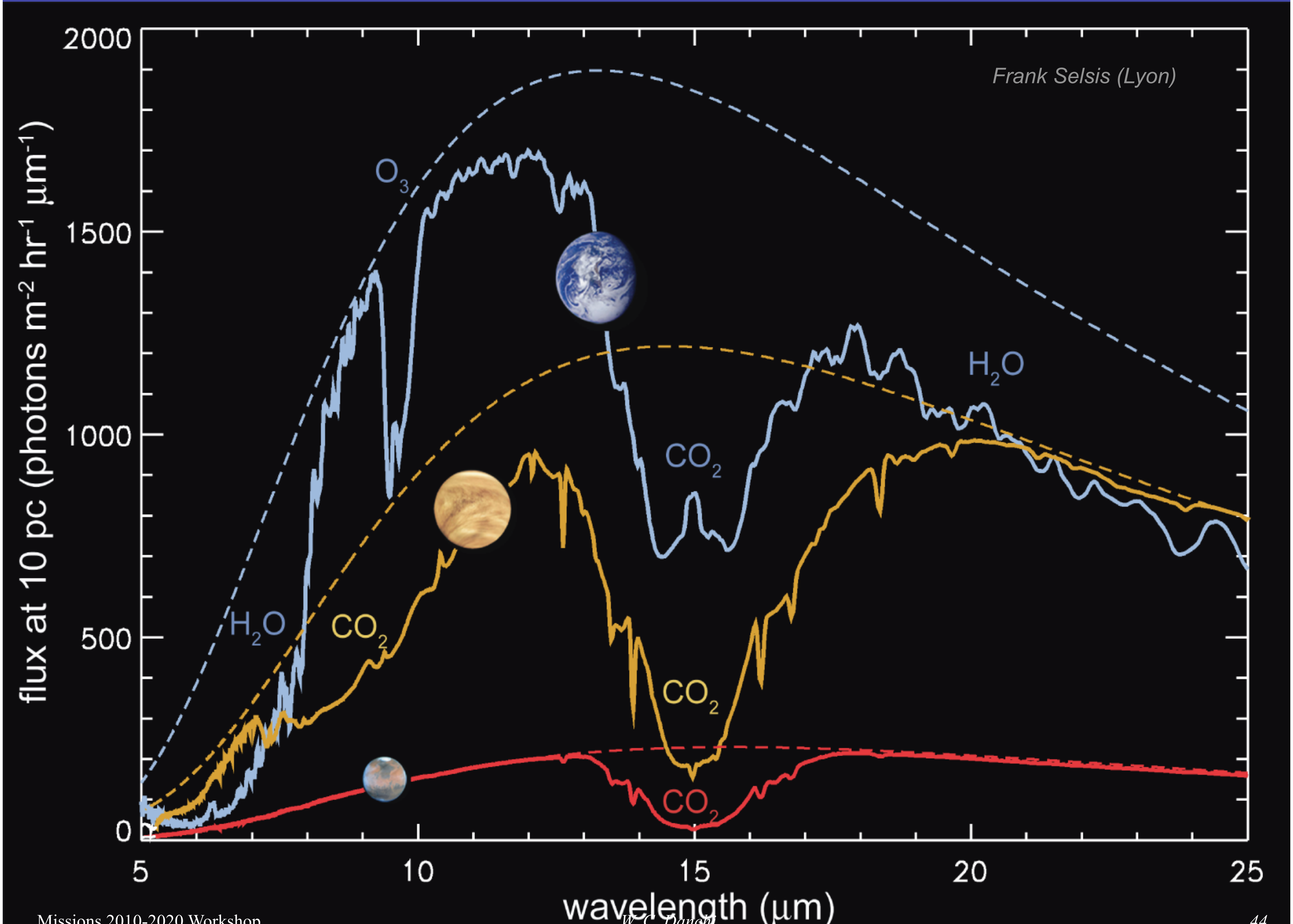
**Milestone #4:** Laboratory demonstration of planet signal extraction with chopping, array rotation, and averaging (Whitepaper signed, 6 May 2008)

**Milestone #5:** Laboratory demonstration of planet signal extraction with spectral filtering and instability noise suppression. (Whitepaper June 2009)

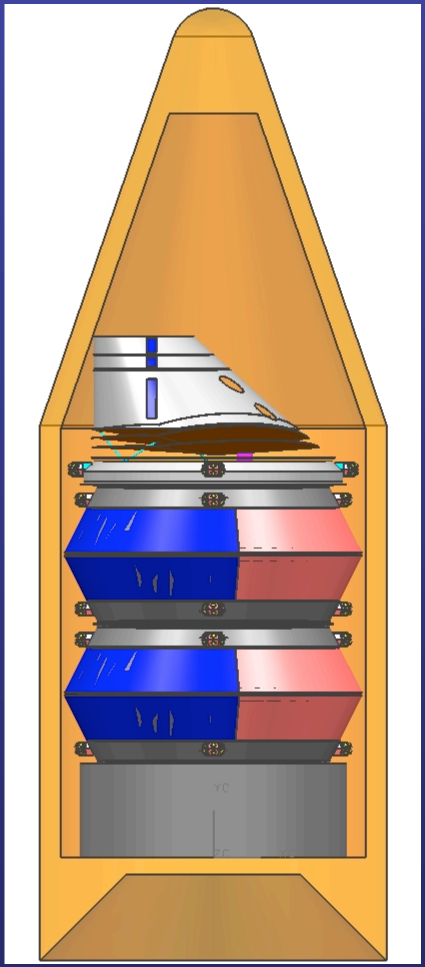
# Interferometer Technology Metrics

| Technology | Specs | Performance to date | Performance target prior to Phase A | Flight Performance (preliminary) |
|---|---|---|---|---|
| Nulling | Average null depth | $9.3 \times 10^{-6}$ (32% BW) Milestone #3 $5 \times 10^{-7}$ (Laser) | $1.0 \times 10^{-5}$ | $1.0 \times 10^{-5}$ |
| | Intensity control | 0.09% Milestone #1 | 0.2% | 0.13% |
| | Phase control | 4.4 nm Milestone #1 | 5.0 nm | 1.5 nm |
| | Stability timescale | 21,600 s Milestone #1 | 5,000 s | > 50,000 s |
| | Bandwidth | 8.4-11.6 μm (32%) Milestone #1 | 8.3 to 10.7 μm (25%) | 7 to 17 μm |
| Formation Flying | Number of S/C | 2 Robots | 3 Robots | 5 S/C |
| | Relative control | 1.4 - 4.6 cm range, 1σ (formation rotation) Milestone #2 | 5 cm range, 1σ (formation rotation) | 2 cm range |



Frank Selsis (Lyon)
flux at 10 pc (photons $m^{-2}$ $hr^{-1}$ $\mu m^{-1}$)
wavelength ($\mu m$)
2000
1500
1000
500
0
5
10
15
20
25
$O_3$
$H_2O$
$CO_2$
$H_2O$
$CO_2$
$CO_2$
$CO_2$

# TPF-I Mass estimates and launch packaging




*Inspired by a design by Thales Alenia Space*

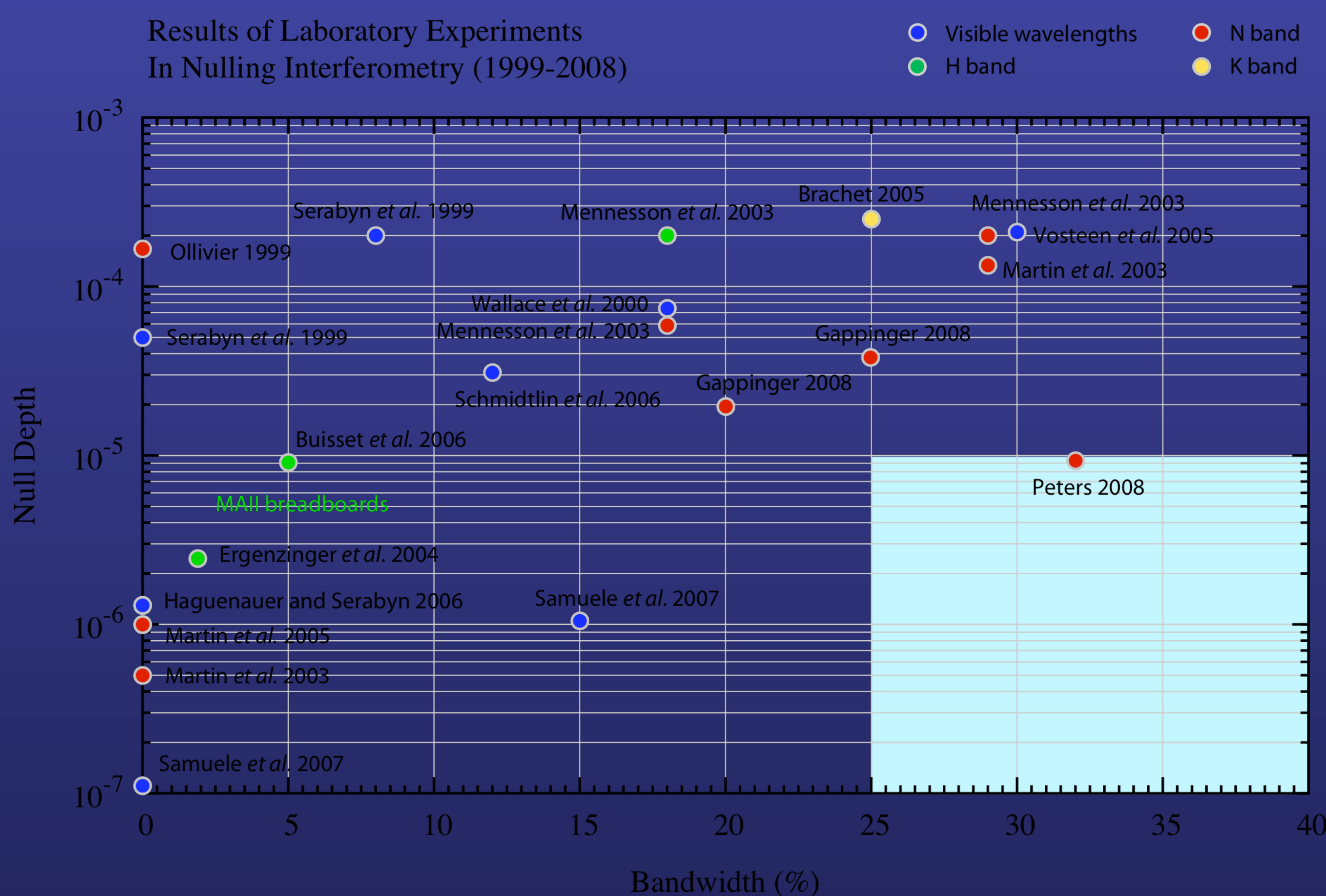
- 3 m design = 6900 kg (w 30% reserve)
- Mass saving of 30% over previous design
- Compatible with medium lift LV
  - Delta IV M+
  - Ariane 5 ECA
- Scaling to smaller diameters
  - 3.0 m 6900 kg
  - 2.0 m 4800 kg
  - 1.5 m 4100 kg
  - 1.0 m 3700 kg

# *ExoPTF Detailed Findings –*
# Nulling IR Interferometer

Since direct detection, either by visible-light coronagraph or infrared interferometer, is the only means to assess Earth-like planet habitability, the decision of which one to fly first should be based on cost and technology readiness at a time when one of the two concepts is ready for implementation. The following actions are therefore recommended :

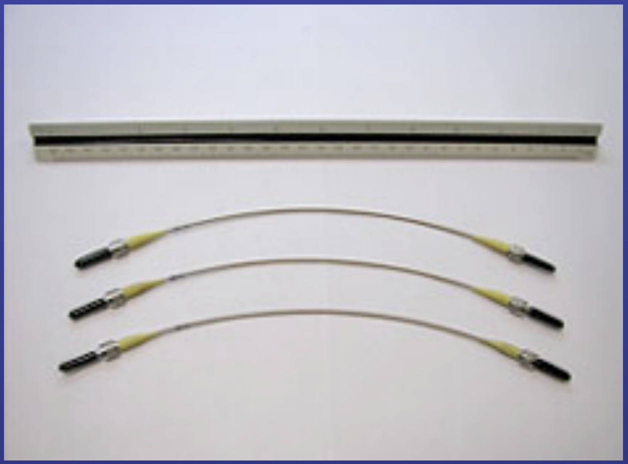
- **Detailed Recommendations on nulling interferometry**
  - The ongoing efforts to characterize the typical level of exozodiacal light around Sun-like stars with ground-based nulling interferometry should be continued.
  - A vigorous technology program, including component development, integrated testbeds, and end-to-end modeling, should be carried out in the areas of formation flying and mid-infrared nulling, with the goal of enabling a nulling interferometry mission around the end of the next decade.
  - The fruitful collaboration with European groups on mission concepts and relevant technologies should be continued.

# State of the Art in Nulling Interferometry



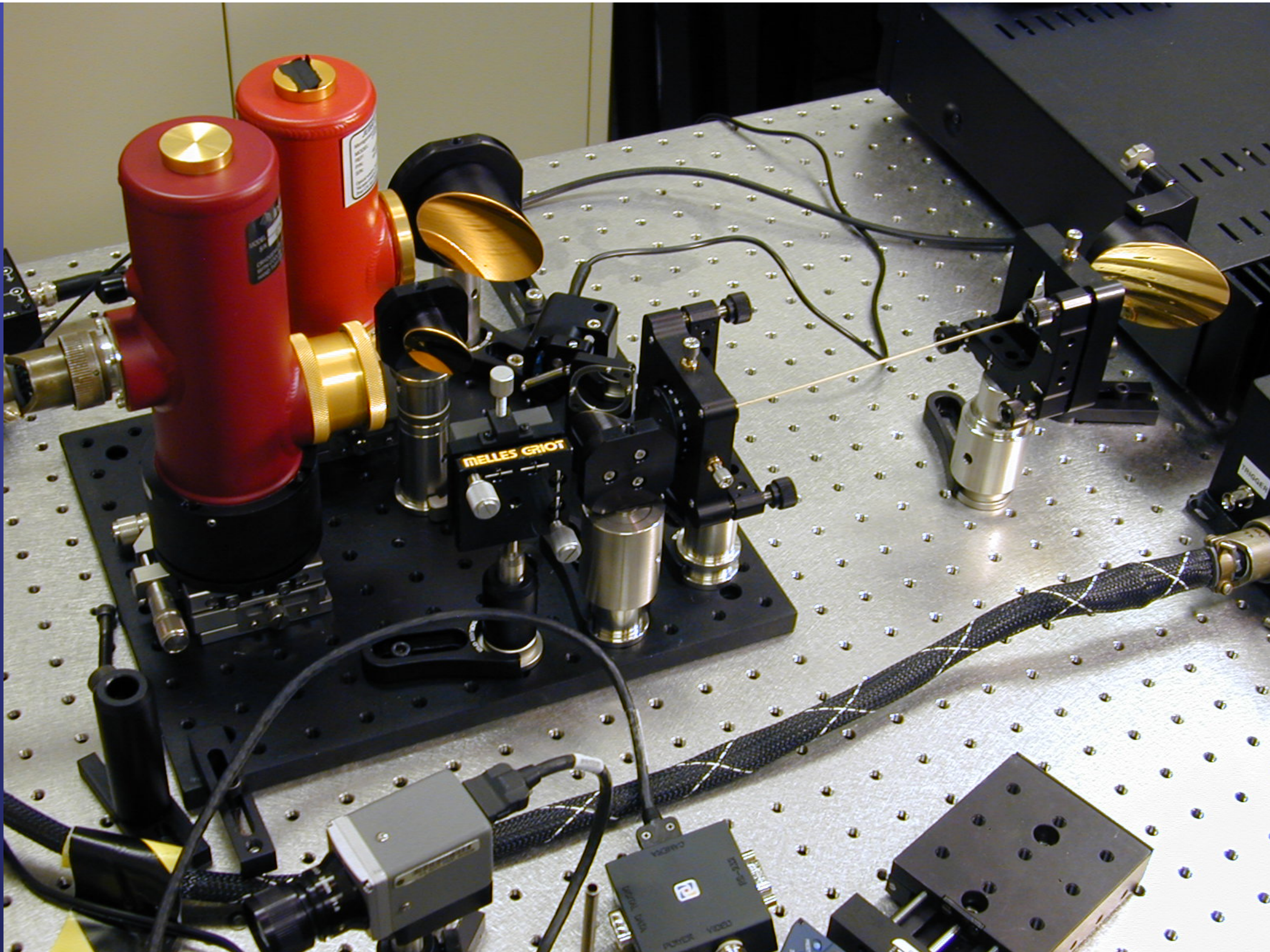
# Single-Mode Mid-Infrared Fibers

- **Chalcogenide Fibers** (NRL)
  - A. Ksendzov et al., “Characterization of mid-infrared single mode fibers as modal filters,” Applied Optics 46, 7957-7962 (2007)
  - Transmission losses 8 dB/m
  - Suppression of 1000 for higher order modes
  - Useable to ~11 microns



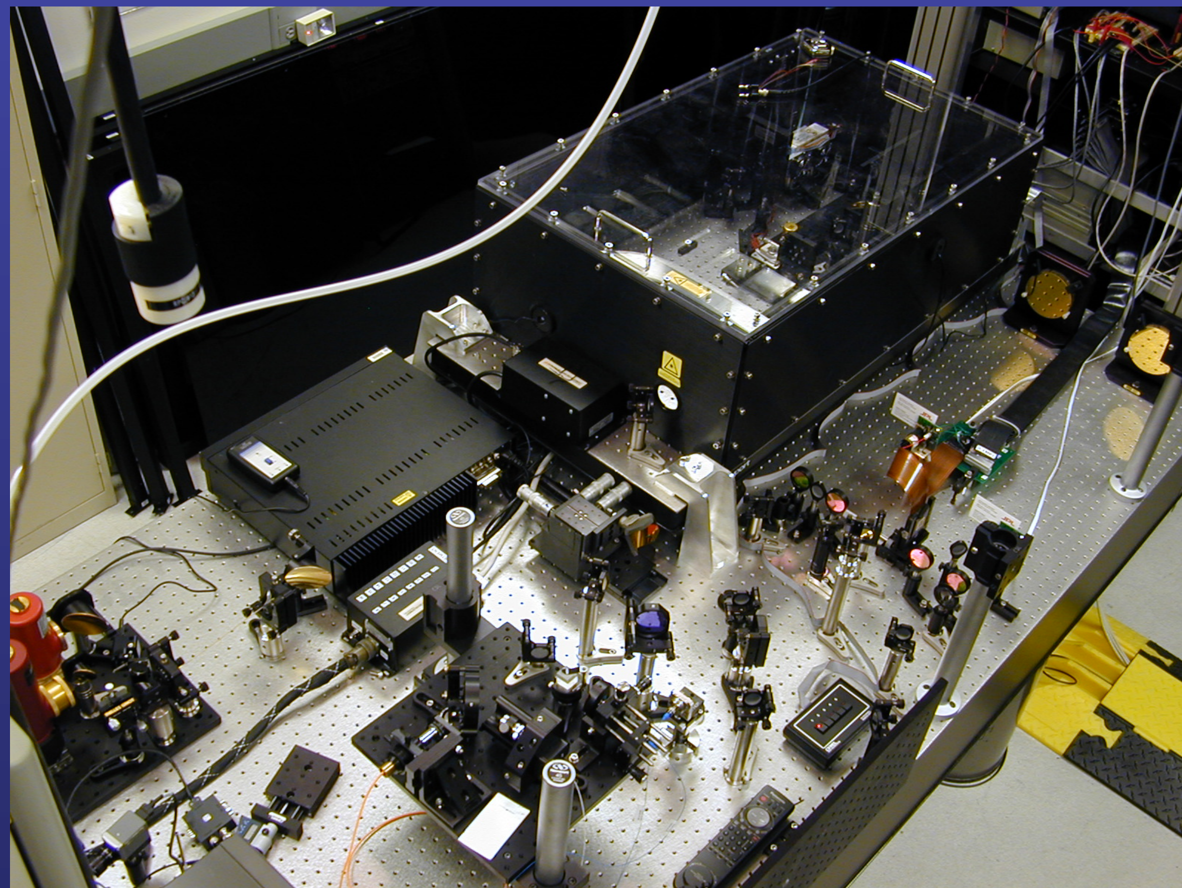
*Example Chalcogenide Fibers, produced on contract by the Naval Research Laboratory*

- **Silver-Halide Fibers** (Tel Aviv Univ)
  - A. Ksendzov et al. “Modal filtering for mid-infrared nulling interferometry using silver halide fibers,” Applied Optics 47, 5728-5735 (2008).
  - Transmission losses 12 dB/m
  - Suppression of 16000 possible with a 10-20 cm fibre, with aperturing the output.
  - Useable to ~18 microns (?)


MELLES GRIOT

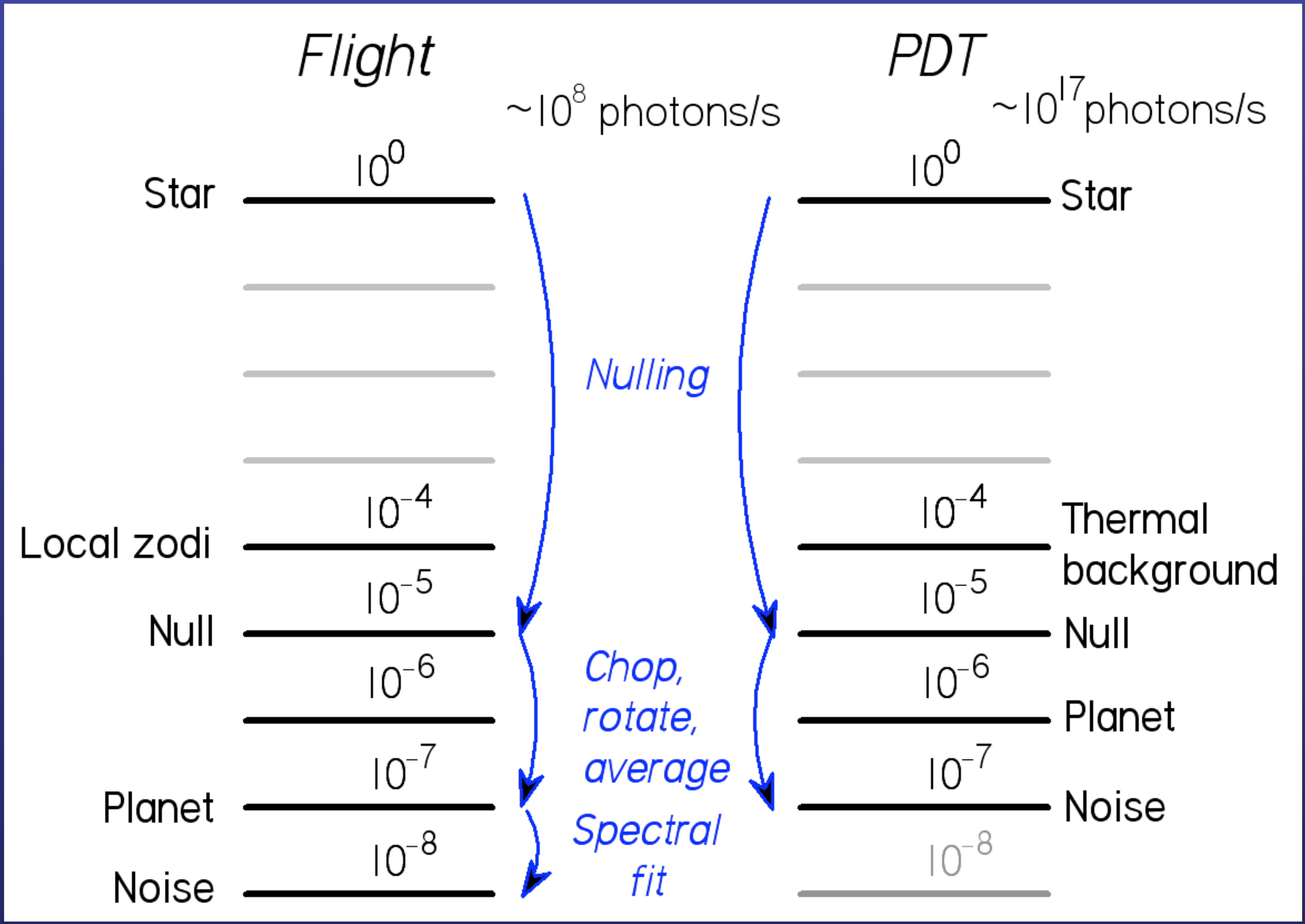
# TPF-I Milestone #1 and #3: Adaptive Nuller

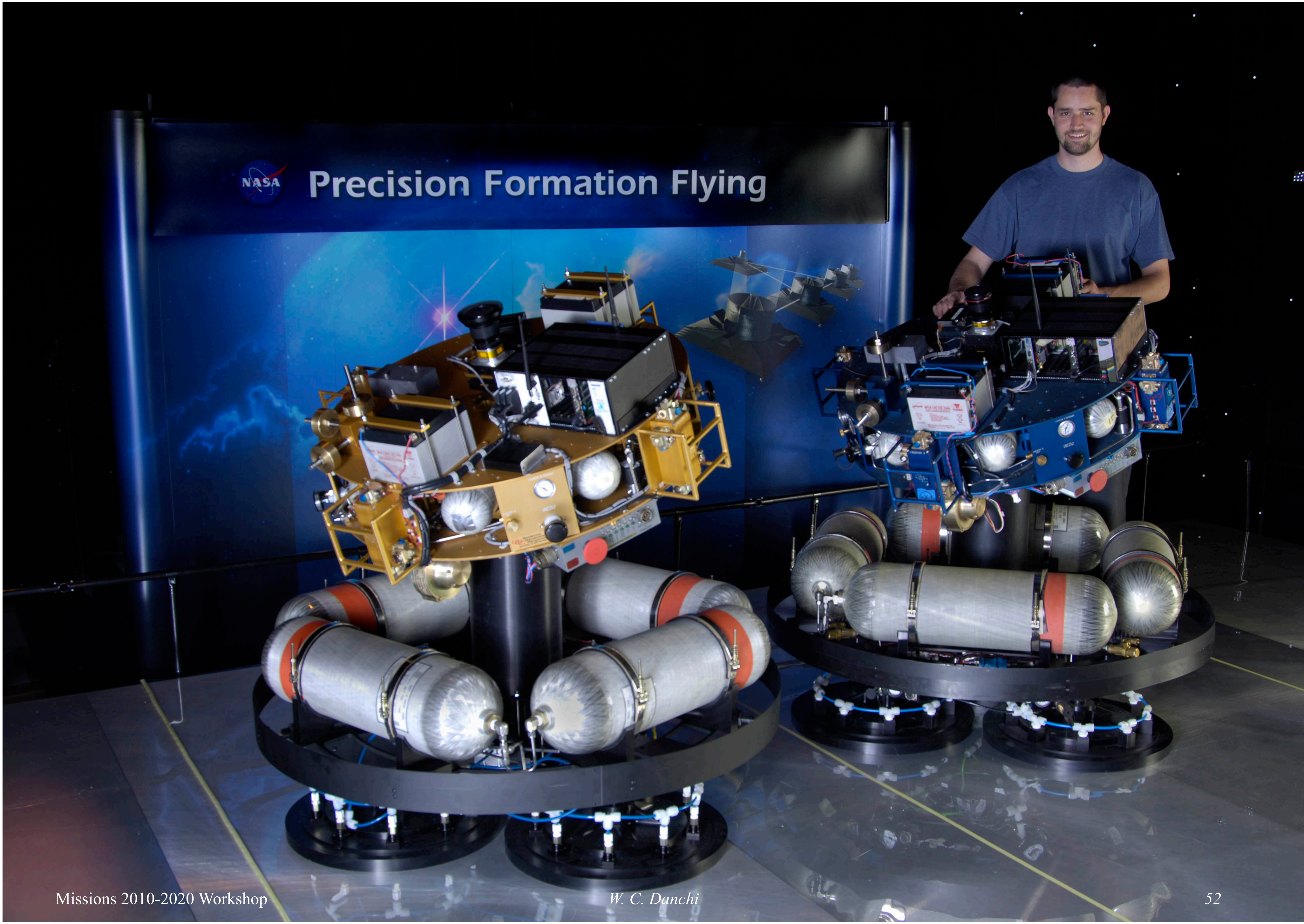
- **TPF-I Milestone #1** completed. The milestone report for the phase and intensity demonstration was approved and signed by NASA HQ, 24 July 2007
  - Demonstrated 0.09% intensity compensation and 4.4 nm phase compensation
- Demonstrated $1.1\times10^{-5}$ mean null depth with a 32% bandwidth, 93% the flight requirements
- TPF-I Milestone #3 whitepaper for broadband nulling demonstration signed 10 October 2007



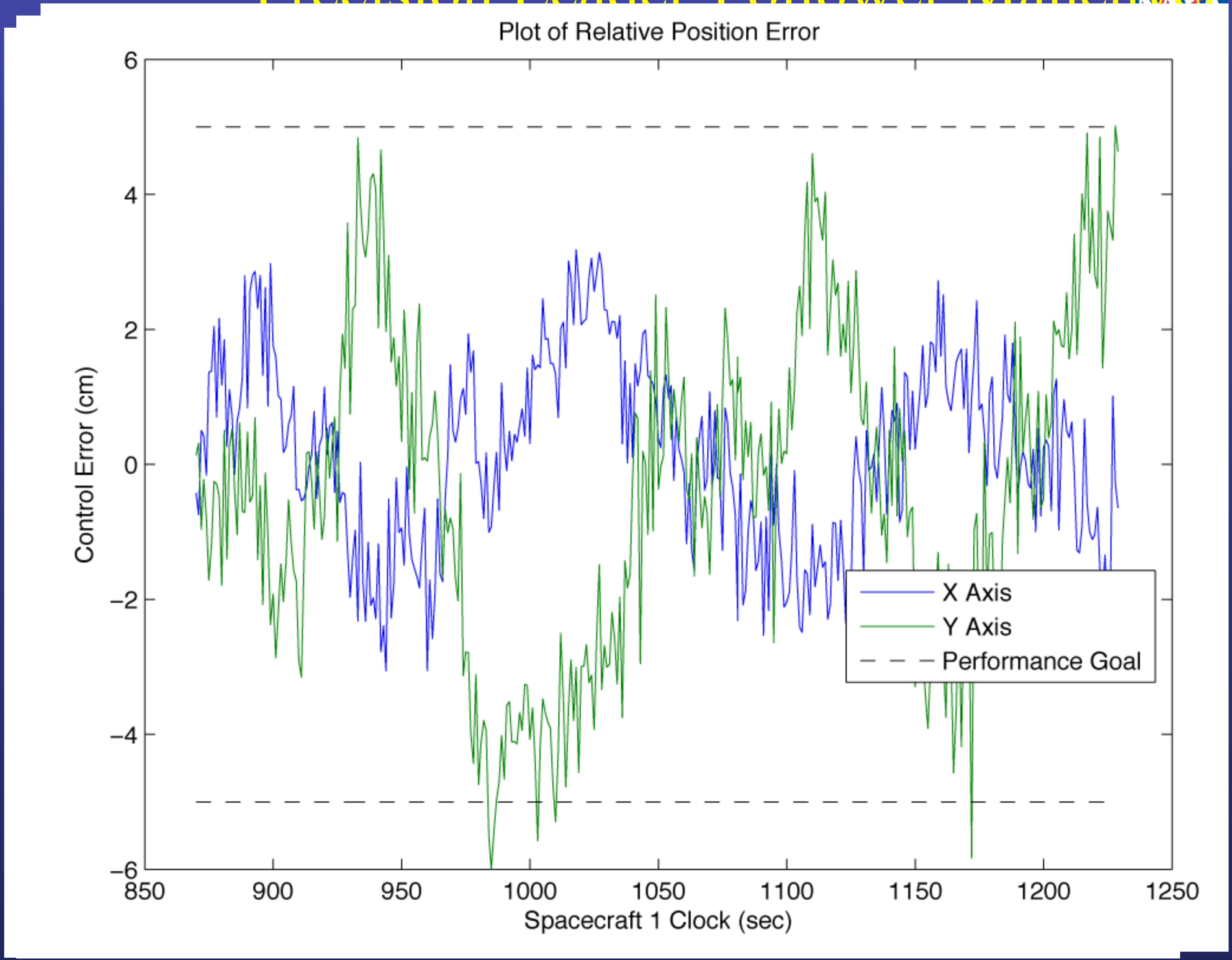
*"Broadband phase and intensity compensation with a deformable mirror for an interferometric nuller,"*
*R. D. Peters, O. P. Lay and M. Jeganathan*
*Applied Optics 47, 3920-3926 (2008).*

# Chop, Rotate, Average, Spectral Fit




NASA
Precision Formation Flying

# Precision Leader-Follower Maneuver



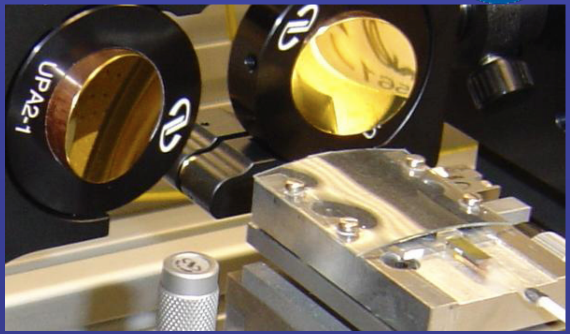
# Recent Advances in Formation Flying

- **Orbital Express** (DARPA) May-July 2007
  - Demonstrated in-orbit servicing of satellites
  - Relative maneuvers of two satellites
  - Transfer of liquids and batteries

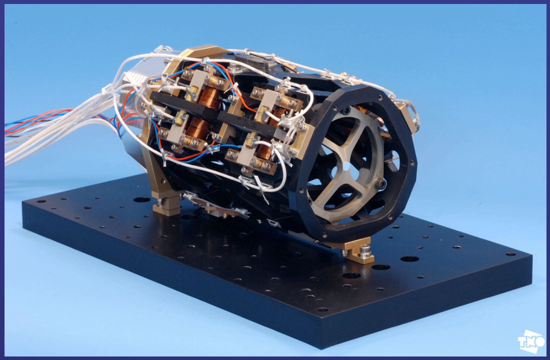
- **Autonomous Transfer Vehicle** (ESA) April 2008
  - Unmanned transport to the International Space Station
  - 10.3-m long and 4.5-m diameter
  - GPS, video, and human supervision
  - Two days of demos, and rendezvous and docking
  - 30 September 2008, completed a destructive re-entry

# Examples of Darwin Technology

- Infrared Nulling testbeds (ESA)
  - Thales Alenia Space
  - EADS Astrium
  - University of Delft
  - Institut d'Astrophysique Spatiale
- Cryogenic Delay Line (ESA)
  - TNO, The Netherlands
- Integrated Optics and Fiber Optics (ESA)
  - LAOG, Université Joseph Fourier, Grenoble
  - Thales Alenia Space
  - EADS Astrium / TNO
  - Université de Rennes
  - Université de Montpellier
- Breadboard demonstrator for PEGASE (CNES)
- Cryogenic mid-IR testbed, Inst. Astrophysique Spatiale (under design)
- RF Metrology for formation flying (Thales Alenia Space)




Thales Alenia Space



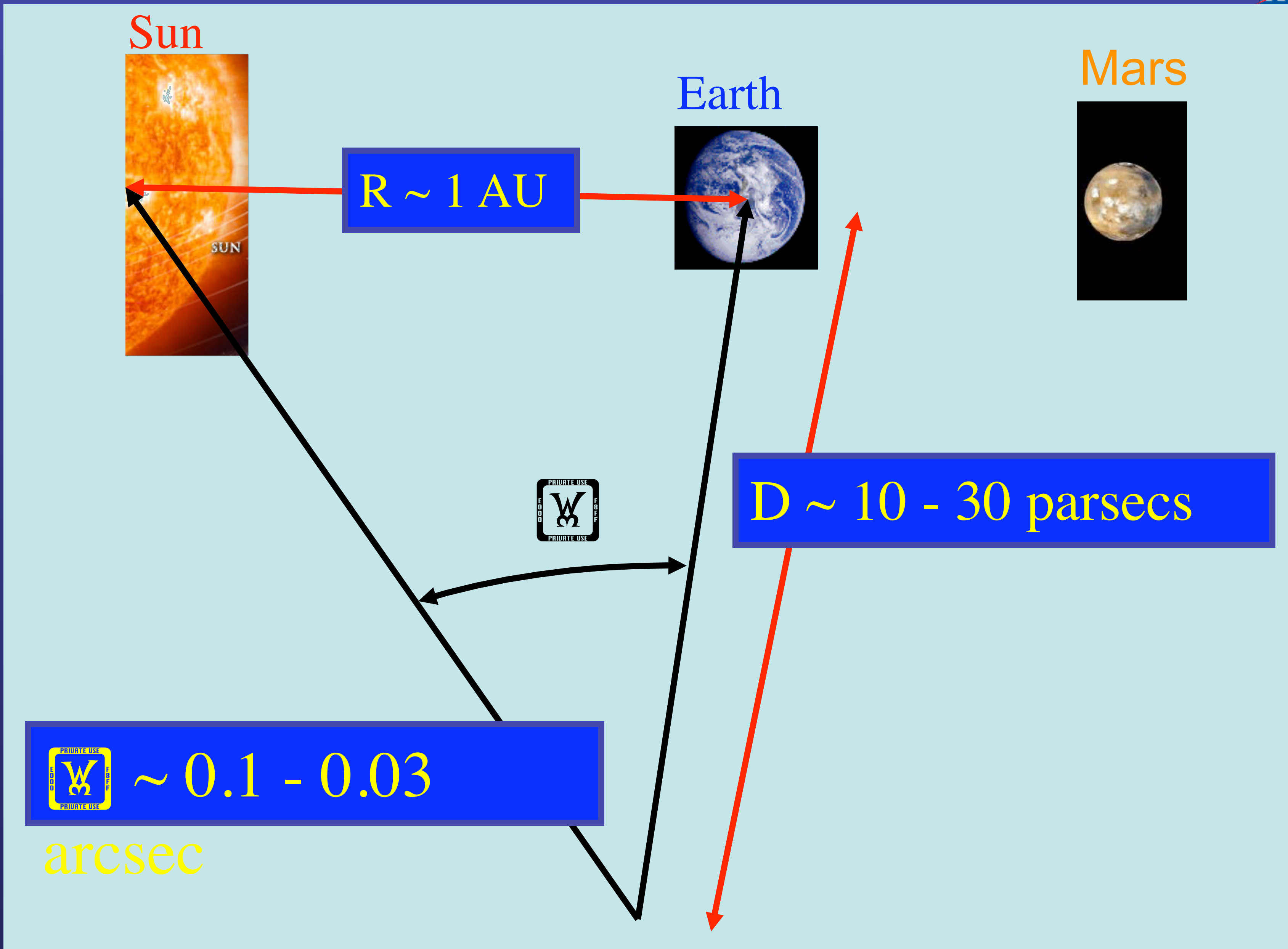
TNO


Inst. Astrophysique Spatiale

# Multi-Aperture Technology

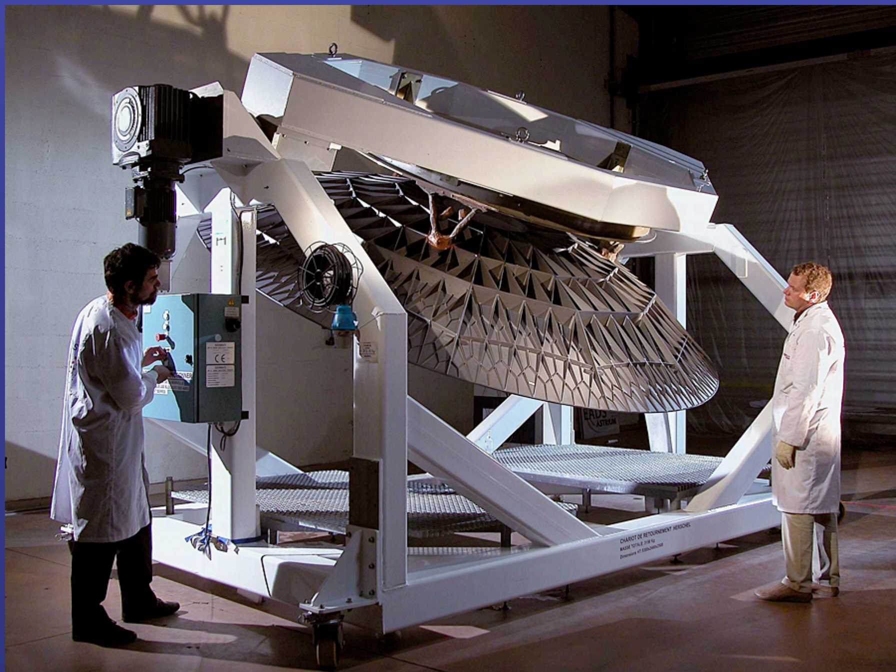
# Backup Slides

# Why high angular resolution is needed



# Single-Aperture Technology

# Large Light-Weight Optics

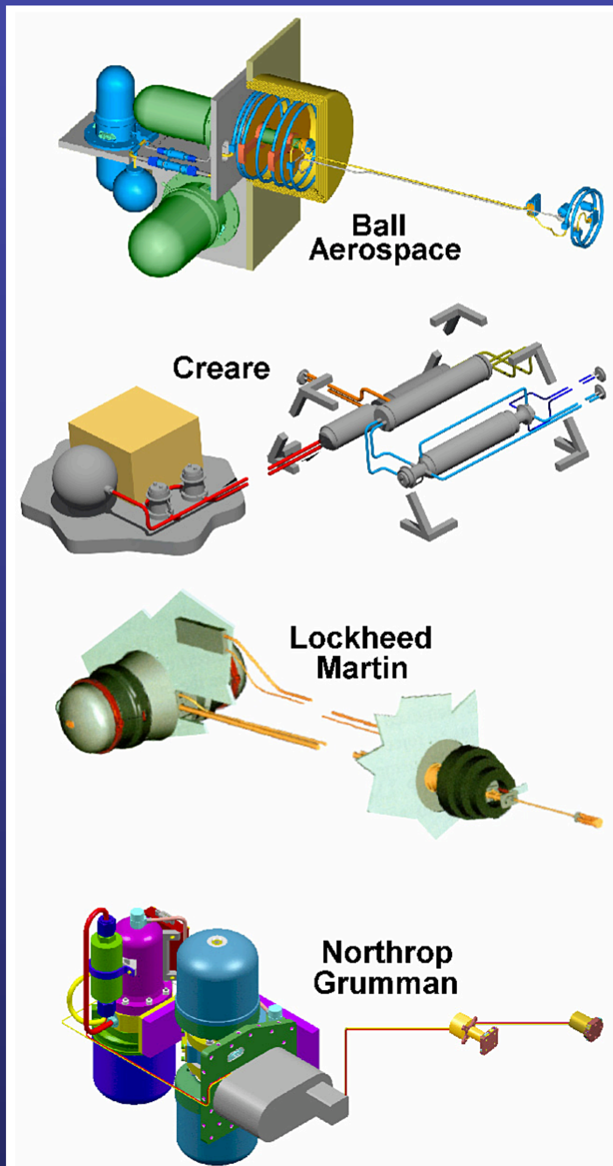


- Herschel Primary Mirror

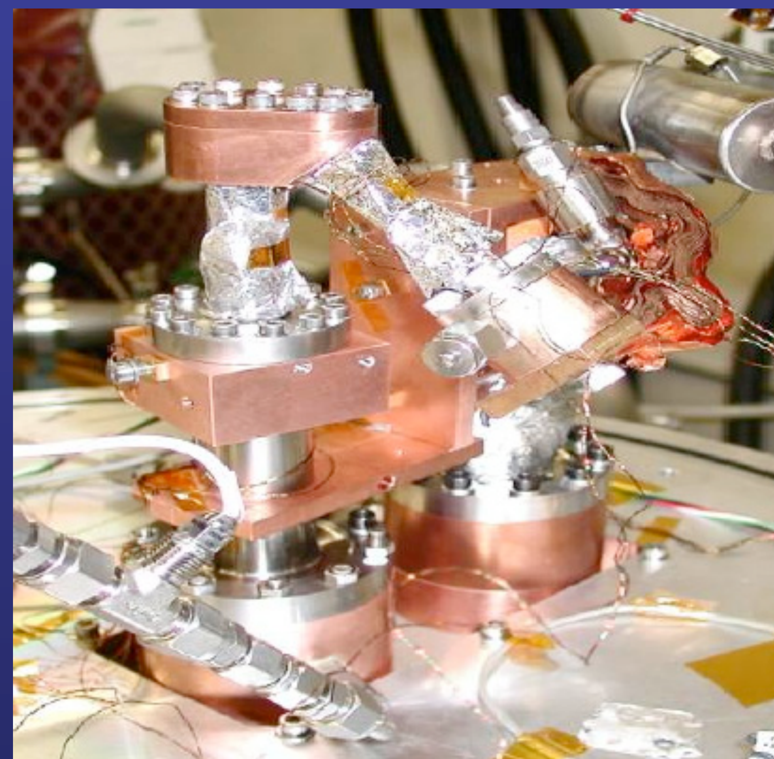
# Passive Cryogenic Cooling

- JWST Sunshield

# Cryocoolers

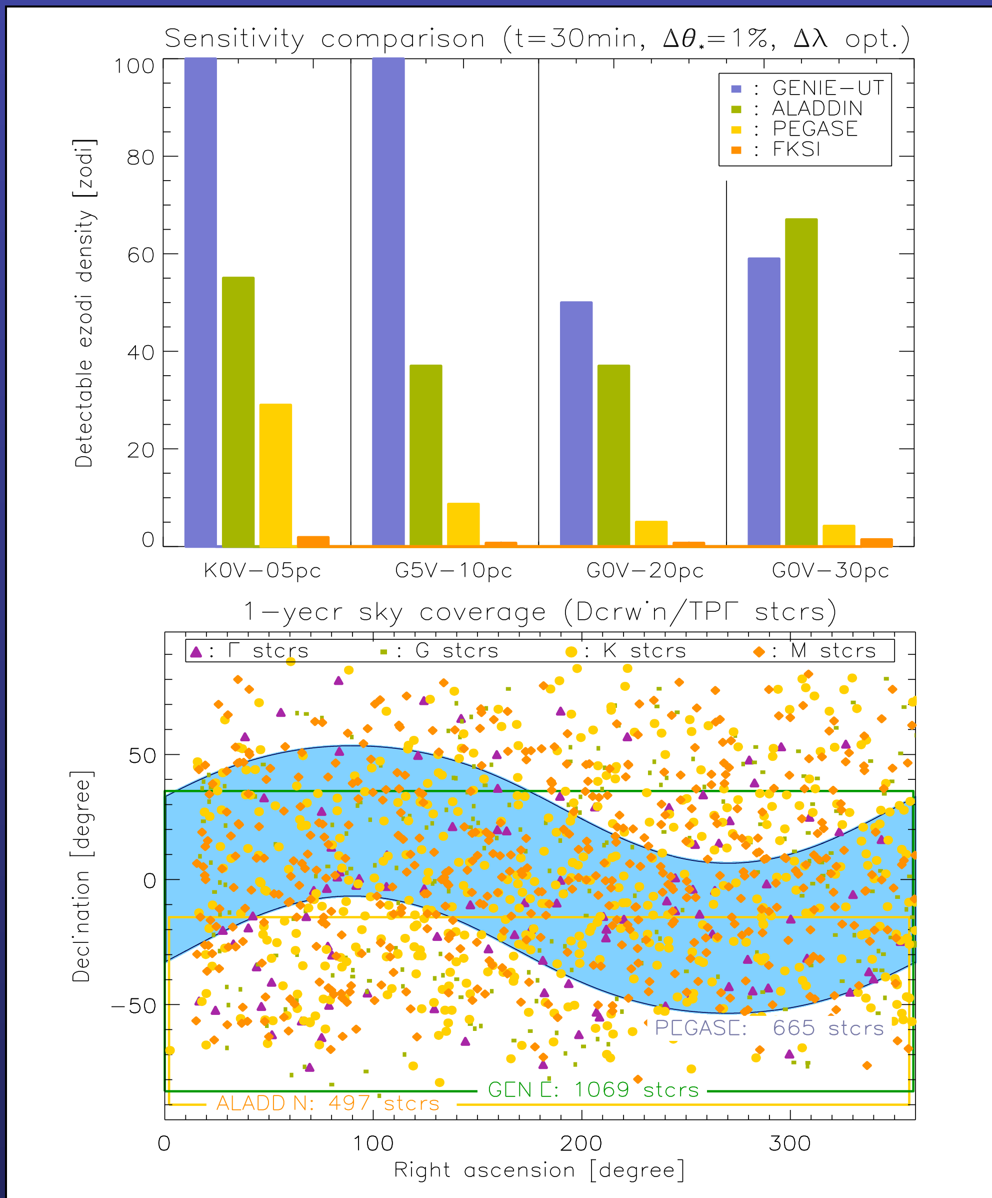



- Advanced Cryocooler Technology Development Program



- JWST Cryocooler (NGST)

# Debris Disk Sensitivity

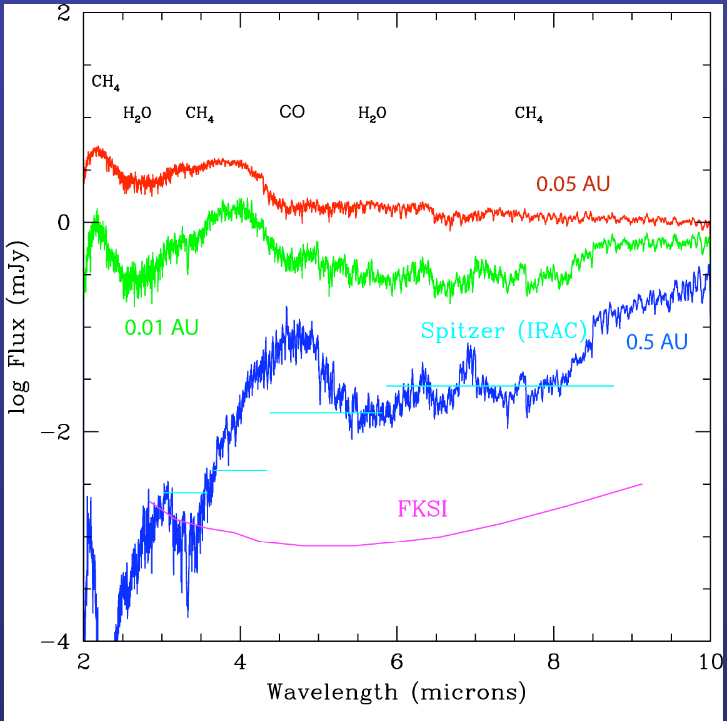



Expected performance for Pegase and FKSI compared to the ground-based instruments (for 30 min integration time and 1% uncertainty on the stellar angular diameters).

Sky coverage after 1 year of observation of GENIE (dark frame), ALADDIN (light frame) and Pegase (shaded area) shown with the Darwin/TPF all sky target catalogue. The blue-shaded area shows the sky coverage of a space-based instrument with an ecliptic latitude in the [-30˚, 30˚] range (such as Pegase). The sky coverage of FKSI is similar to that of Pegase with an extension of 40˚ instead of 60˚

# Exoplanet Characterization with a Small Structurally Connected Interferometer

| Orbital Parameters | What FKSI does: |
|---|---|
| Removes sin(I) ambiguity | Measure |
| **Planet Characteristics** | |
| Temperature | Measure |
| Temperature variability due to distance changes | Measure |
| Planet radius | Measure |
| Planet mass | Estimate |
| Planet albedo | Cooperative |
| Surface gravity | Cooperative |
| Atmospheric and surface composition | Measure |
| Time variability of composition | Measure |
| Presence of water | Measure |
| **Solar System Characteristics** | |
| Influence of other planets, orbit coplanarity | Estimate |
| Comets, asteriods, zodiacal dust | Measure |

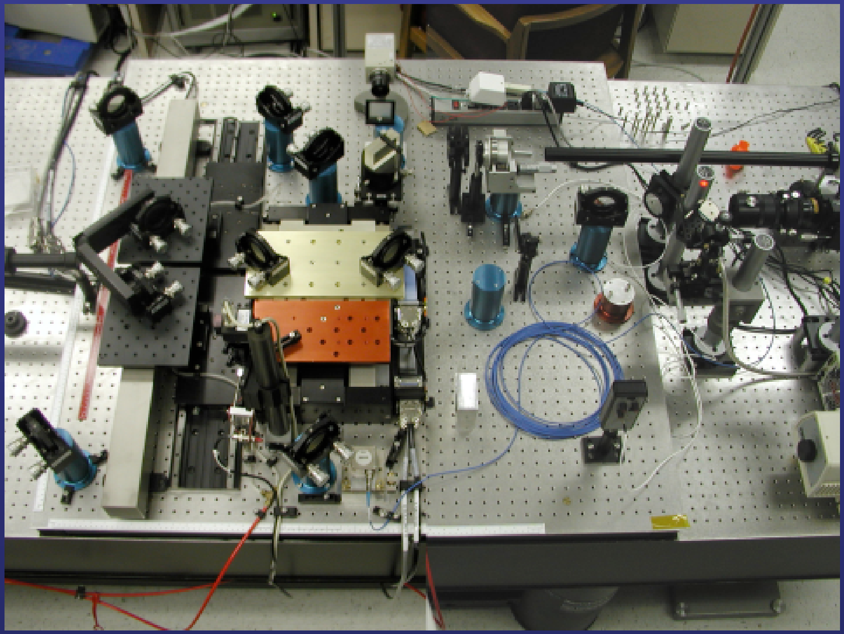


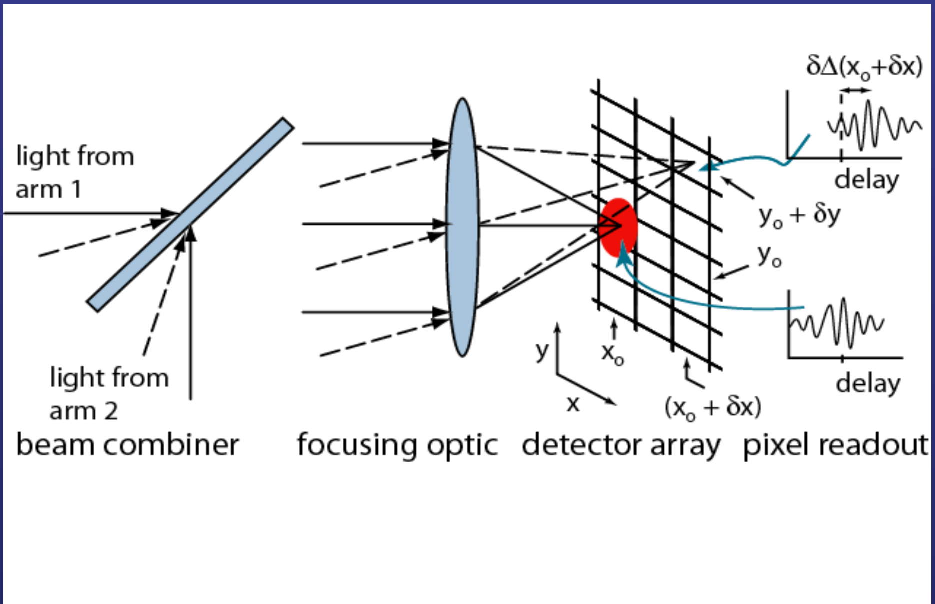

Left panel. Characteristics of exoplanets that can be measured using FKSI. (b) Right panel. The FKSI system can measure the spectra of exoplanets with a wide range of semi-major axes.

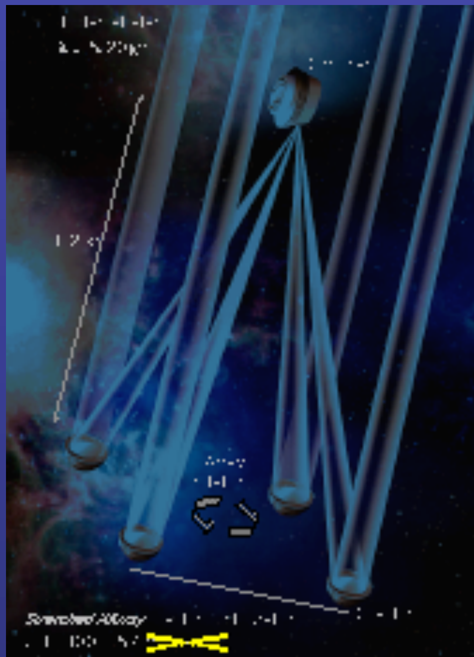
# Wide-Field "Double Fourier" Interferometry in the Lab

The **Wide-field Imaging Interferometry Testbed (WIIT)** was built to develop a wide field-of-view optical/IR imaging interferometry technique

A detector array is substituted for the single-pixel detector used in a conventional Michelson (pupil plane) beam combiner, and a scanning optical delay line is used to provide spectroscopic information and compensate for external delay

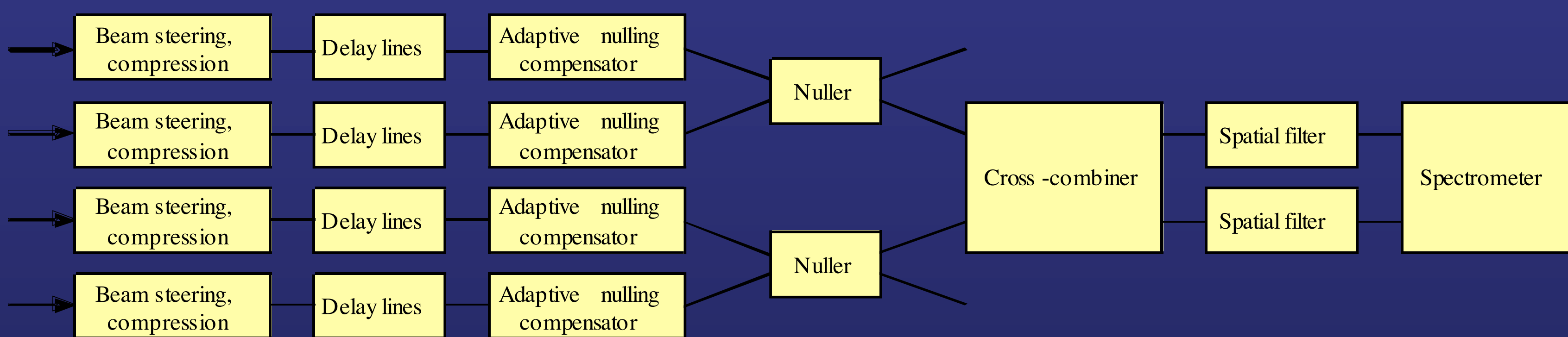






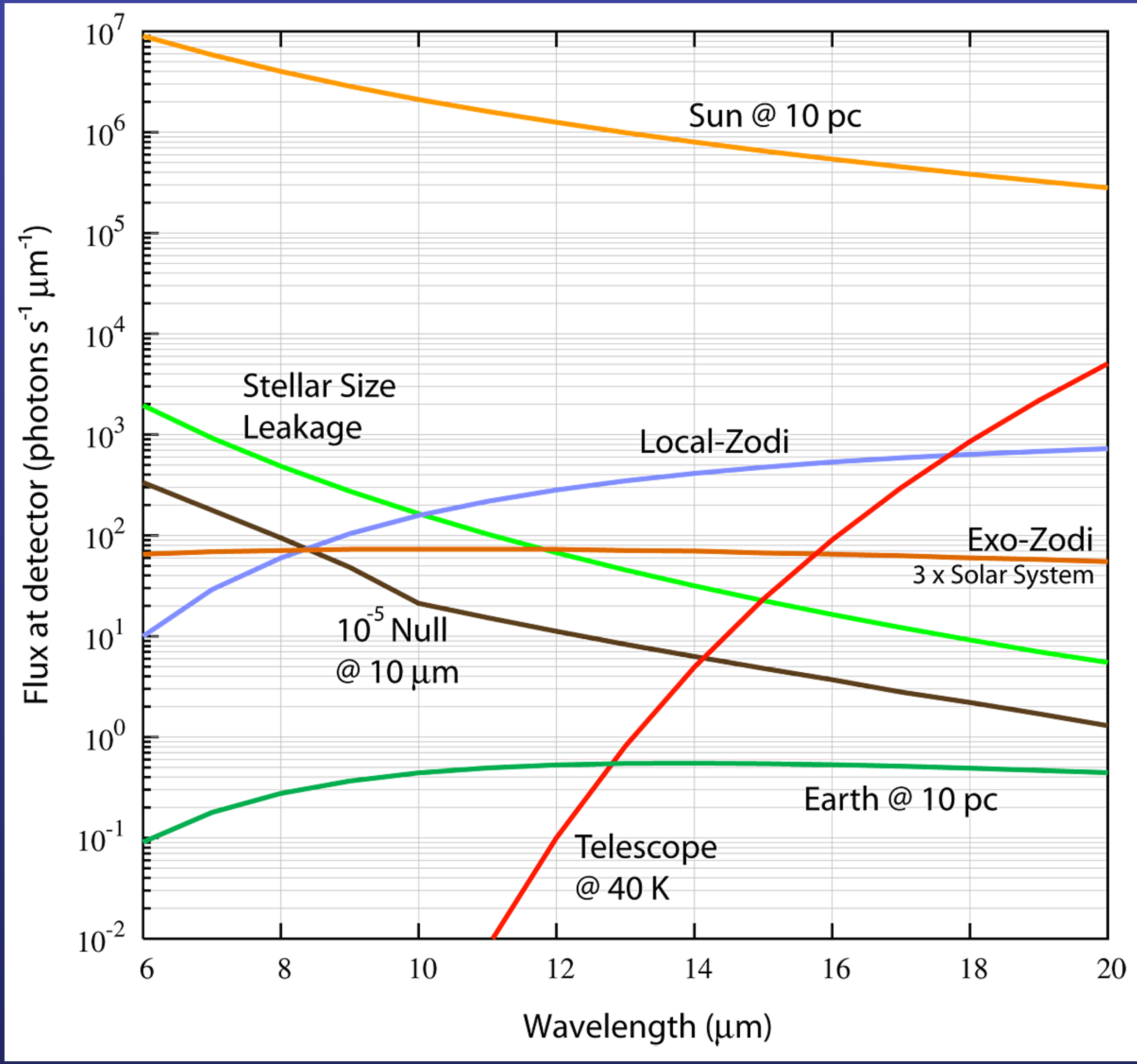
# TPF Architecture

Emma X-Array Architecture resulted from detailed studies of the past several years




Schematic of beam combiner optics

# Sources of Noise at Mid-Infrared Wavelengths

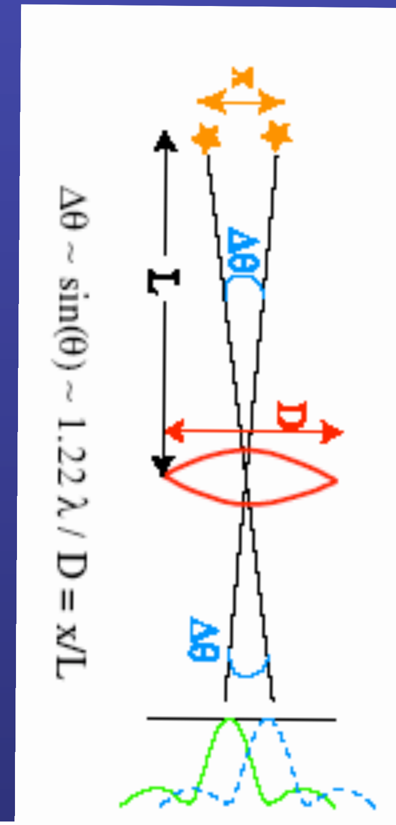


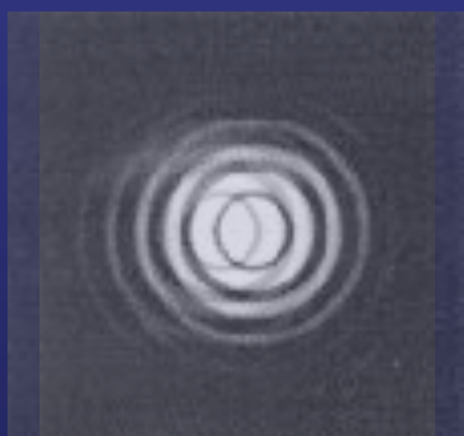
# Resolution of a conventional telescope: Rayleigh Criterion

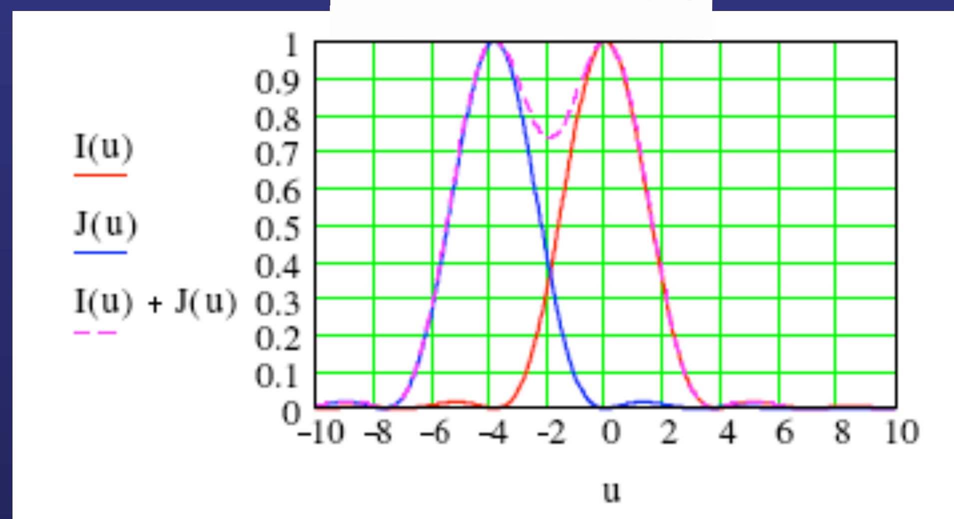
[illegible][illegible] ~ 1.22 [illegible] / D

l = wavelength of light

D = telescope diameter

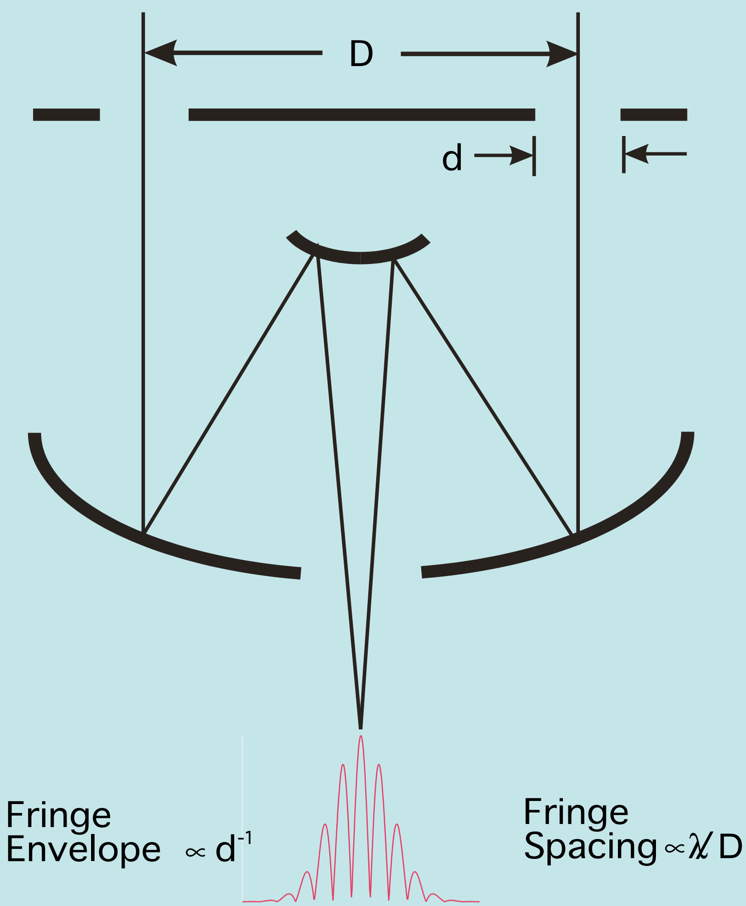


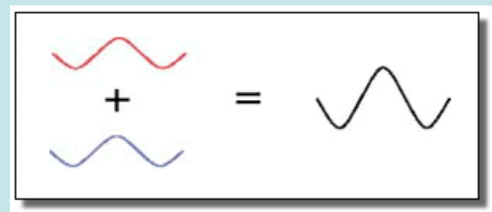


# A simple interferometer

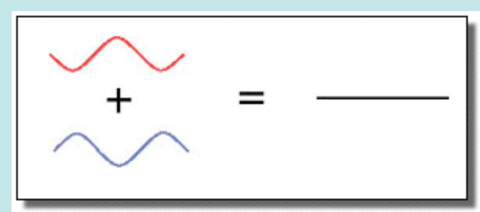
Simplest Interferometer -- Aperture Masking




•You get a peak when pathlengths are equal on both sides -- "white light fringe"




•You get a null when pathlengths differ by one half a wavelength -- a "dark fringe"



# Interferometer Resolution

**Interferometer Resolution is:**

$\lambda/(2B)$ where $\lambda$ is wavelength and B is the baseline.

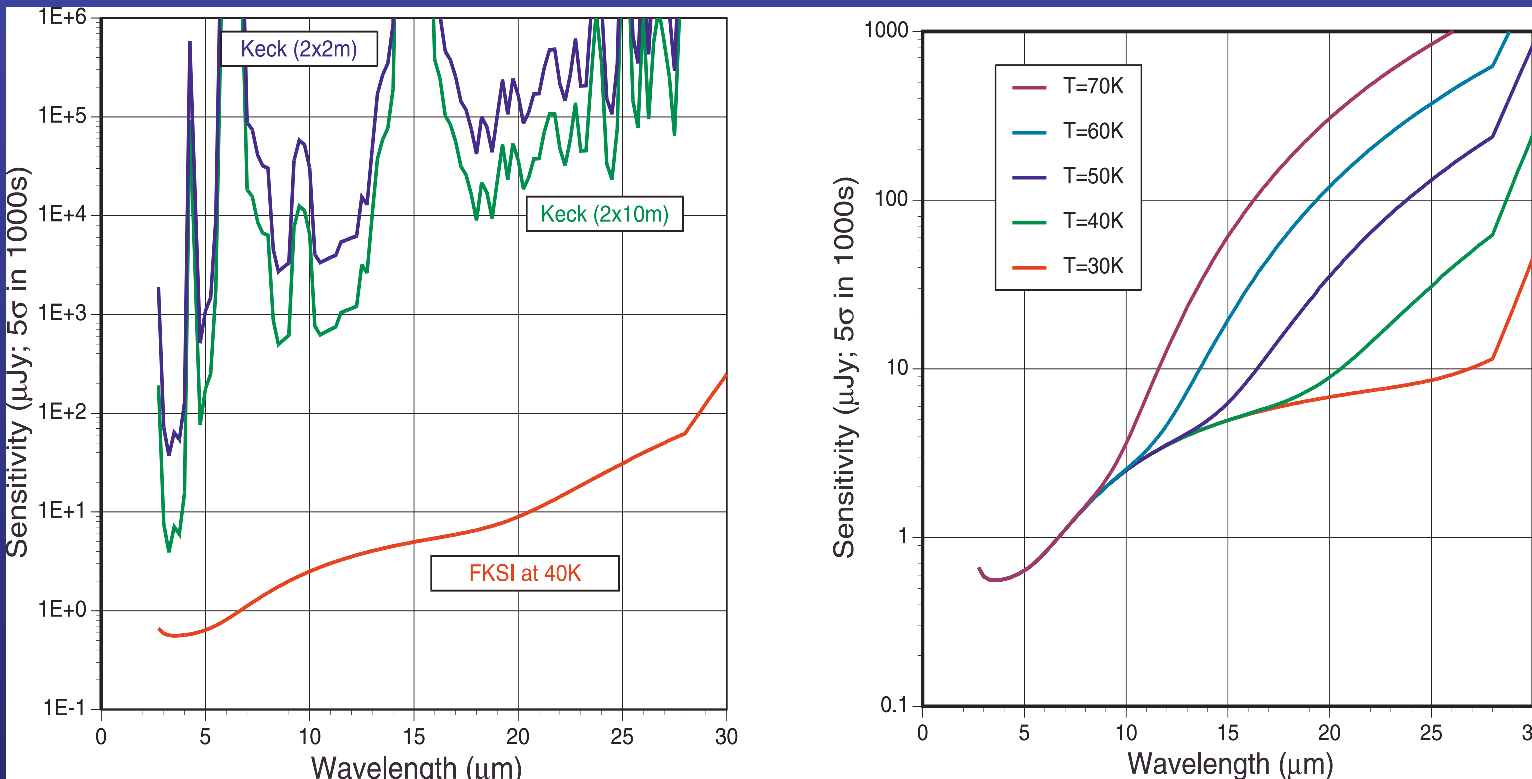
For 100 mas resolution --> B = 10 m at 10 μm

10 mas resolution --> B = 100 m at 10 μm

***This sets the minimum baseline size***.

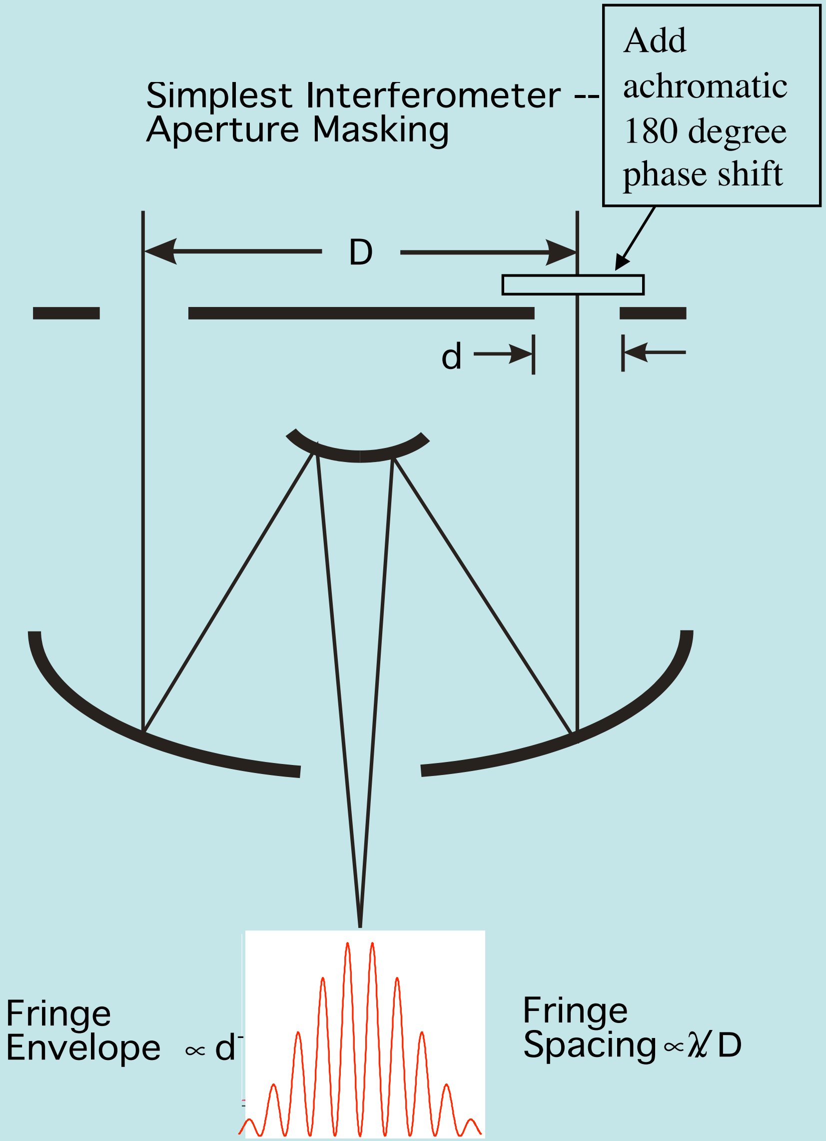
*A 20-40 m baseline at 10 μm is adequate resolution for a substantial number of nearby F,G,K, stars, or 1/2 that if the center wavelength is 5 μm.*

# A SMALL Cooled Space Telescope is Very Sensitive Compared to a LARGE Ground-based Telescope

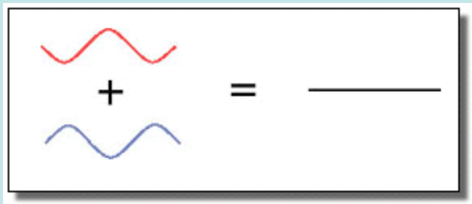



**Left panel** . The sensitivity of the FKSI system (1 m telescopes) with telescope temperature at 40 K compared to either two 10 m Keck telescopes or two Keck 2 m outrigger telescopes.
**Right panel**. Effect of telescope temperature on FKSI sensitivity.

# A simple nulling interferometer




•You get a null when pathlengths are equal on both sides -- “white light null fringe”




•You get a peak when pathlengths differ by one half wavelength -- a “bright fringe”